Hydrogeology of the

Cromwell Terrace Aquifer,

Central Otago.

A Thesis

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Frontispiece

Sarita Orchards irrigation pond, Cromwell Flat.

Abstract

A hydrogeologic model, groundwater chemistry and stable isotopic analysis were used to establish recharge resources and outflows so a water balance could be developed for the Cromwell Terrace Aquifer (CTA) in Central Otago, New Zealand. Increased popularity of the Central Otago region for viticulture, orcharding and tourism, has resulted in an increased demand for water. Groundwater is a viable option to meet this demand for water.

The CTA is a single unconfined aquifer contained within a thin veneer of permeable Quaternary glacial outwash gravels that range in thickness between 10 and 50m. These gravels rest unconformably on less permeable folded Tertiary sediments. The buried surface of the Tertiary sediments is irregular and provides the main hydrogeologic control in the CTA. Buried topographic highs in the Tertiary sediments impede groundwater flow, while the buried paleochannels at the southern end of the Cromwell Flat allow groundwater to flow unrestricted. The saturated thickness of the aquifer varies between 10 and 30 m.

The direction of groundwater flow is in south easterly and south westerly directions toward both Lake Dunstan and the Kawarau Arm respectively. This indicates that recharge is from the Pisa Range. Annual fluctuations in groundwater levels show that there is a seasonal effect on the groundwater table. Annual fluctuations in groundwater level are in the range of 0.4 – 0.5 m, with lowest levels in winter and highest groundwater levels in late summer. The higher groundwater levels in summer correlate with when higher rainfall occurs, but could also be due to artificial recharge from irrigation during summer, and/or seepage from the Ripponvale Irrigation Scheme canals and storage ponds.

Groundwater chemical analysis showed the dominant facies to be calcium bicarbonate waters. The source of the calcium bicarbonate is considered to be calcite in the Otago Schist, with concentrations of calcium bicarbonate being higher closer to the bedrock schist of the Pisa Range. Concentrations decreased toward Lake Dunstan, where calcium bicarbonate concentrations were lowest. The trend of calcium bicarbonate concentrations decreasing toward Lake Dunstan produces a similar pattern to the direction of groundwater flow. This would suggest that calcium bicarbonate concentrations are being diluted by rainwater infiltrating into the aquifer. However stable isotopic analysis showed that lake water infiltrates into the aquifer around the lake margin, and would also dilute calcium bicarbonate concentrations.

Stable isotopic analysis found that groundwater was more depleted in both $\delta^{18}O$ and $\delta^{2}H$ than water from Lake Dunstan. The average $\delta^{18}O$ for groundwater was -9.5‰, whereas the average $\delta^{18}O$ for

samples from Lake Dunstan was -8.1‰. The average $\delta^{18}O$ value of Pisa Range snow, Pisa Range streams and Cromwell Flat precipitation gave values of -9.2‰ +/- 1.4‰, which is very similar to groundwater. This suggests recharge to the CTA is from a combination of snow melt and surface stream flow from the Pisa Range, and some direct rainfall infiltration on the Cromwell Flat.

A water balance was calculated for the CTA groundwater system using the information from this study, and from a limited Otago Regional Council (O.R.C.) database. The main inputs to the CTA were found to be recharge precipitation and subsurface flows from the Pisa Range. The main outputs were identified as surface evaporation and discharge from the CTA to Lake Dunstan. The water balance showed that the total flow of water through the CTA is 93 Million cubic metres per year (Mm^3/yr).

At present the CTA has limited groundwater allocation measures in place. Using the information from the water balance, a volume of groundwater that could be abstracted sustainably was estimated. This volume was estimated using the O.R.C. method of allocating 50% of the mean annual precipitation that recharges the aquifer for groundwater abstraction. The total mean annual precipitation for the Cromwell Flat and Pisa Range is 20 Mm^3/yr. Using the 50% of mean annual precipitation method, 10 Mm^3/yr can be allocated for groundwater abstraction. The total volume of groundwater currently abstracted is 3 Mm^3/yr, leaving 7 Mm^3/yr of unallocated groundwater. Due to the small land area, types of land use, low population density of Cromwell Flat and availability of surface water (i.e. Lake Dunstan), it is unlikely that the total volume of 10 Mm^3/yr will be fully allocated.

Acknowledgements

I would like to thank the Otago Regional Council and in particular Jens Rekker for suggesting this project, providing valuable data and information, and advice which made this thesis possible. It has been a great opportunity and is much appreciated. I would especially like to thank the many landowners across the Cromwell Flat as without your permission to access your land to take water samples and measurements, I would not have been able to complete this thesis. Many thanks to Graham Stewart of McNeil Drilling in Alexandra for providing bore log details, equipment and a personal tour of the Cromwell Flat, Royden Thompson for helping me out with a number of questions about the area, and the Farrelly family for kindly providing me with a place to stay while carrying out field work in Cromwell. I would also like to thank my supervisors David Bell and Travis Horton at the University of Canterbury for helping arrange this project, carrying out analysis of samples and reviewing draft chapters. To Cathy Higgins and Anekant Wandres, thank you for helping organise equipment for field work and providing technical support for ArcGIS. Many thanks to Alison Roberts and Janet Warburton for helping me sort out Mason Trust and enrolment issues. To the College of Science ladies, especially Tracey Robinson and Isobel Philips, thank you for helping sort out enrolments and other paper work involved with completing this thesis. I would also like to thank my office mates, Rob Hunter, Malcolm Hicks and Hayden McKenzie for your patience in allowing me to bounce ideas of you. Lastly many thanks to mum, family, friends and any one else who I may have forgotten to thank.

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Chapter One

Introduction

1.1 Project Background

Cromwell Flat is located in Central Otago and is approximately 70 km to the east of Queenstown, in South Island of New Zealand (Figures 1 and 2).

The Central Otago region has produced large quantities of alluvial gold and was once famous as gold rich region (Turnbull & Forsyth, 1988). At present, Central Otago is an extremely popular tourist and holiday destination due to its history with gold mining, as well as its location, scenery and climate. It is this later factor that has seen the increased development of land for orchards, vineyards and lifestyle blocks. The increased land use has led to an increased demand for fresh potable water, with a large majority of water being supplied from surface water flows and precipitation, as well as groundwater extraction.

The Cromwell Flat area sources its water supply from the unconfined Cromwell Terrace Aquifer (referred to here on as the CTA) and surface water takes from Lake Dunstan.

Groundwater extraction from the CTA is monitored and controlled by the Otago Regional Council (Referred to as the O.R.C.), but current allocation limits are only estimates.

The Cromwell Flat is surrounded by Lake Dunstan which borders the Flat on two of its sides. Lake Dunstan was created in the early 1990’s as part of a hydroelectric power scheme. The filling of the lake has resulted in the groundwater level being raised. Information about the source of recharge to the aquifer is lacking, along with a water balance and a hydrogeological model of the CTA.

1.2 Project Aims

The main objective of this project is to determine the inflows and outflows of the CTA, and to evaluate how the CTA interacts with Lake Dunstan. Once these factors are known a water balance for the CTA can be calculated so a sustainable water allocation scheme can be created for the Cromwell Flat. A combination of water contour maps, stable isotopic analysis, water chemistry and a hydrogeologic model has been used to try and identify the inflows and outflows of the CTA. These will also determine the flow paths of the aquifer and how Lake Dunstan interacts with the aquifer.

1.3 Study Area

Cromwell Flat is located at the confluence of the Kawarau and Clutha Rivers, at the southern end of the Cromwell – Tarras Basin (Beanland & Berryman, 1989). Cromwell Flat is bordered by the Kawarau and the Clutha Rivers on the southern and eastern sides. The Pisa Range and foothills border the Cromwell flat on its western and northern sides respectively. These borders act as the study boundaries for the Cromwell Flat, although the catchment for recharge to the aquifer extends up onto the Pisa Range and the foothills. The regional location of the Cromwell is shown in figure 1.1 and a detailed map of Cromwell Flat is displayed in figure 1.2.

Cromwell Flat is mostly occupied by orchards, vineyards and lifestyle blocks scattered across its surface with the most developed area being the Cromwell Township. Cromwell Township is located at the north east corner of the Flat and has a population of 3,585 but can expand to upwards of 7000 during holiday periods (Statistics New Zealand, 2006).

In the late 1970's and early 1980's the Clyde Hydroelectric project began, and by the early 1990's was completed. This resulted in the formation of Lake Dunstan, a 26.4 km^2 lake stretching from Luggate (near Wanaka) and the Kawarau Gorge outlet to the township of Clyde. The filling of Lake Dunstan resulted in the water level of the Clutha River and Kawarau River in the Kawarau Arm being raised by 60m (Branson & Bailey, 2009; Contact Energy, 2010). The effect of this was the groundwater level of the CTA being raised, making the depth to water shallower. Little information is known about how Lake Dunstan interacts with the groundwater of the CTA and any implications it has had on the aquifer.

Presently, the Otago Regional Council (Referred to as the O.R.C.) has not carried out a water balance for the groundwater resource of the Cromwell Flat. The present groundwater allocation scheme for the CTA employed by the O.R.C. stipulates that groundwater abstractions <25 m^3/day are permitable without resource consent, but any larger extractions (>25 m^3/day) require resource consent and O.R.C. must be notified (Jens Rekker, pers comm, 2011). O.R.C. estimates that approximately 3 Mm^3 of groundwater is extracted per annum. This allocation scheme is based on a notional estimate of 50% of natural recharge to the Cromwell Terrace Aquifer (referred to here on as CTA) (Jens Rekker, pers comm, 2011).

Figure 1.1 – Location map of Cromwell and surrounding areas.

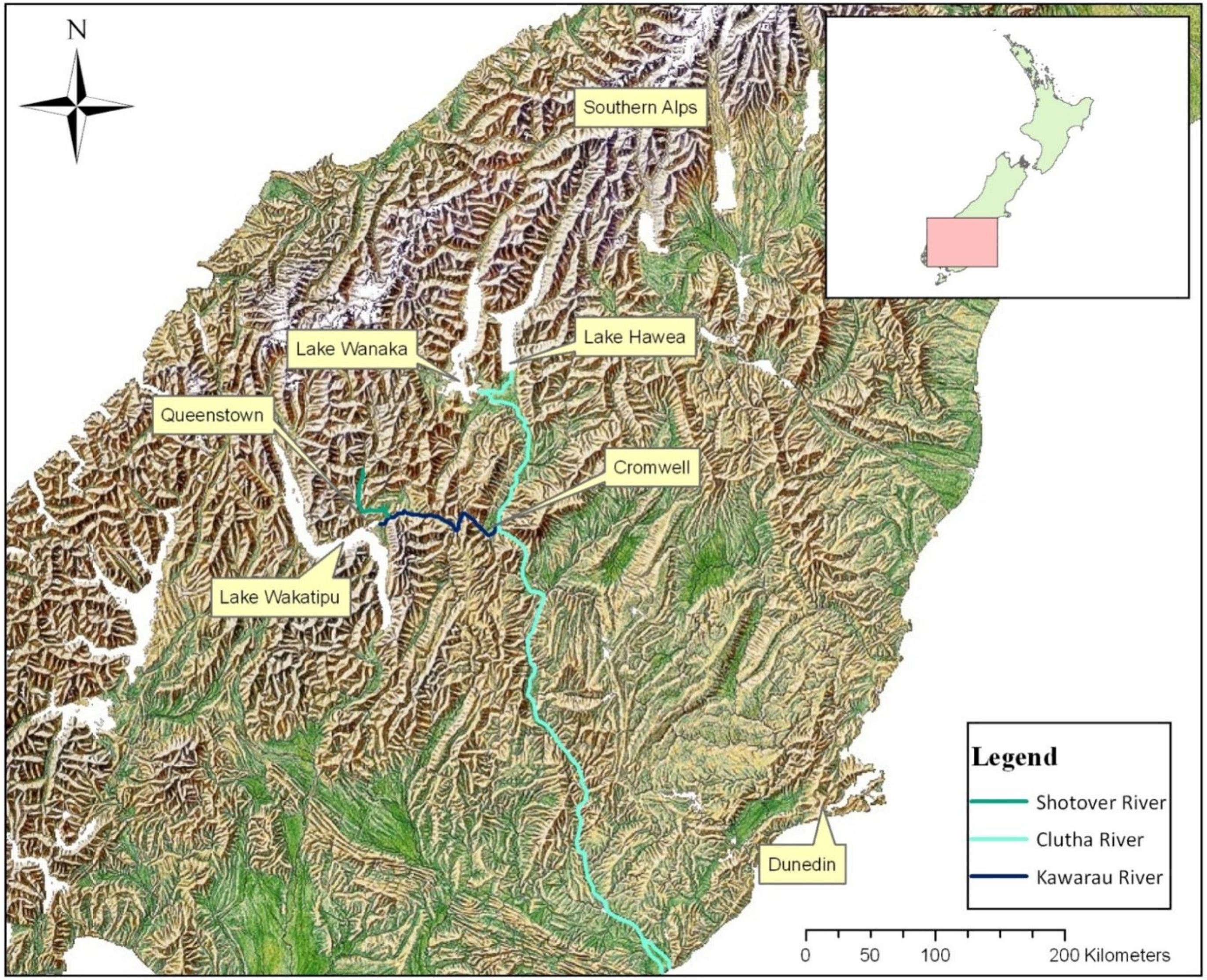
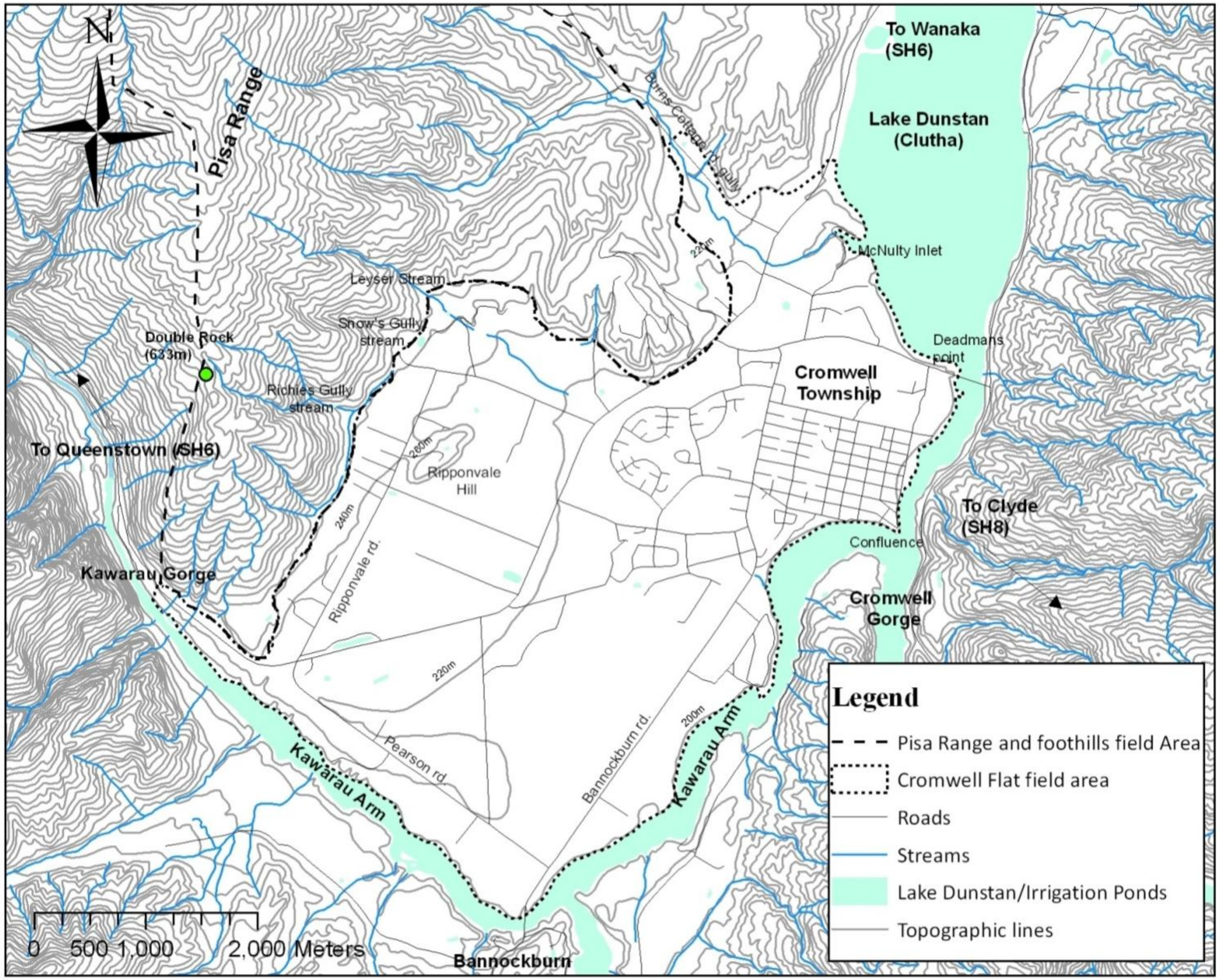


Figure 1.2 – Map of Cromwell Flat and Lake Dunstan



1.4 Physical Setting

1.4.1 General Setting

The Cromwell Flat is an undulating surface with a surface area of 24 km^2 that slopes gently toward the east at an angle of approximately 1-2°, with elevations ranging between 200 masl and 260 masl. It is predominantly made of Quaternary outwash gravels from a number of glacial episodes further up the Cromwell – Tarras basin and from the Kawarau River catchment. There is a single unconfined aquifer that exists beneath the Cromwell Flat in these Quaternary gravels known as the Cromwell Terrace Aquifer or CTA. The gravels of the CTA typically range in thickness from 10 – 20 m thick but can reach 50 m thick in places. The Pisa Range behind the Cromwell Flat (western boundary) rises quickly from the valley floor and is composed of Otago Schist of the textural zone IV. It has an approximate slope angle of 20°, and reaches elevations of 1600 masl.

The foothills and older terraces at the northern end of the Cromwell Flat are composed of Tertiary lacustrine and fluvial deposits and are capped by older Quaternary outwash gravels.

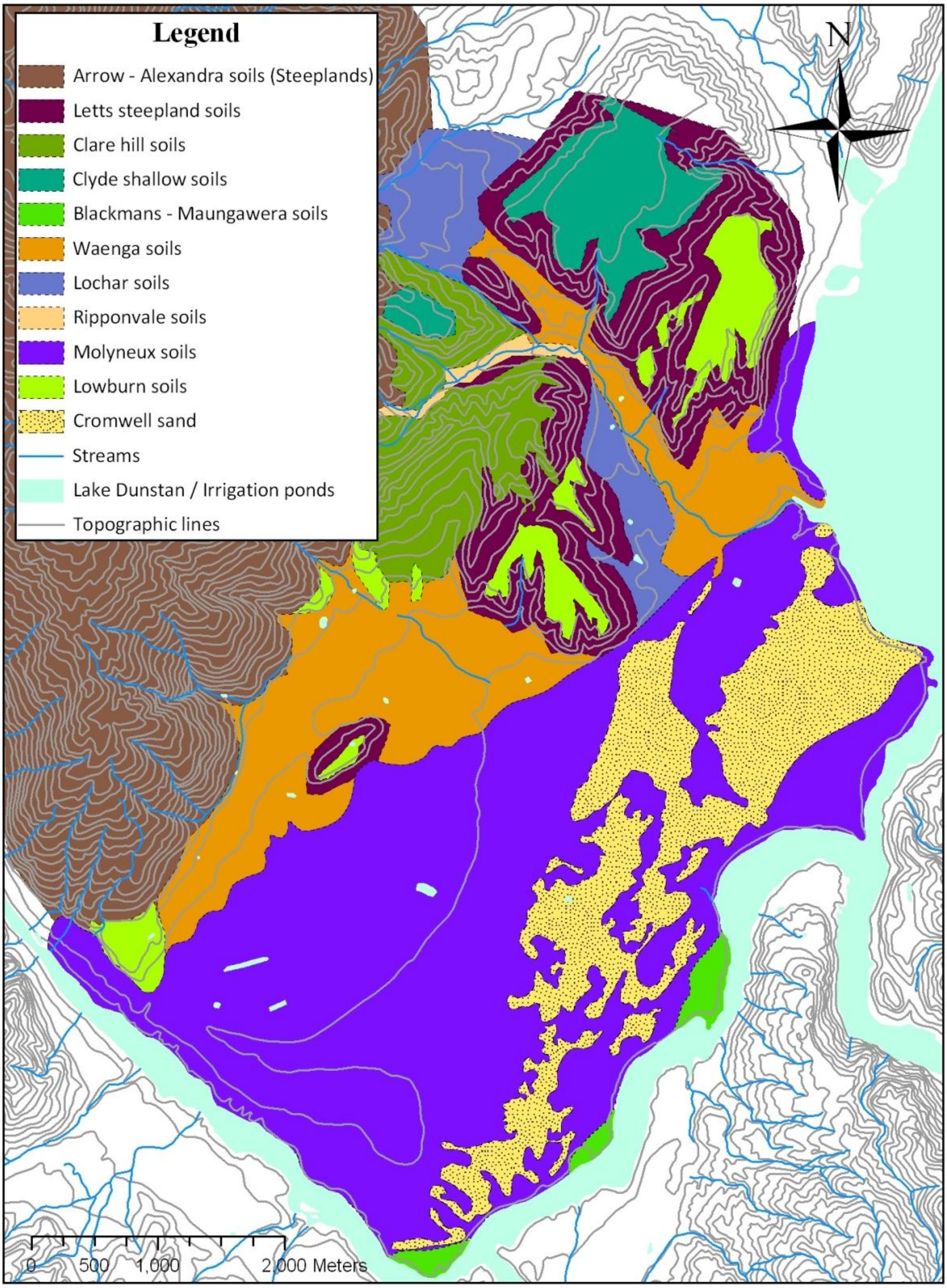
There are 3 main streams that flow off of the Pisa Range (Riches Gully Stream, Snow's Stream and Leyser Stream) toward the back of the Cromwell Flat, but no active streams flow across the terrace. These streams have very low flow rates, with a combined average of 88 m^3/day, but have increased flows during large thunderstorms in the warmer months (Rickard & Cossens, 1968).

1.4.2 Soils

The soils of the Cromwell Flat have been described in detail by Leamy and Saunders (1967) and by Rickard and Cossens (1968). A map of the Cromwell Flat soils is shown in figure 1.3. Descriptions of the soil types from Leamy and Saunders (1967) are provided in appendix 1.4.2.

The Cromwell Flat soils have developed on top of permeable outwash gravel and fan deposits. The dominant soil type for the Cromwell Flat is the Molyneux soils. These soils are formed from the mixing of loess with schist and greywacke gravels sourced from the Quaternary outwash gravels beneath them (Leamy & Saunders, 1967). On the northwestern side of the Cromwell Flat the Waenga soils cover alluvial fans at the base the Pisa Range. These soils are a mixture of loess, colluvium and alluvial material sourced from the narrow stream gullies on the Pisa Range (Leamy & Saunders, 1967; Rickard & Cossens, 1968). Beneath the Cromwell Township and along the eastern margin of the Flat, the Cromwell sand is the prominent soil (Leamy & Saunders, 1967). This sand was sourced from the 1878 flood deposits, and was progressively moved from the Clutha River valley floor up on to the Cromwell Flat via aeolian processes (Cockayne, 1911; Park, 1908).

Figure 1.3 – Soil map showing soil type and distribution of soils across the Cromwell Flat. Adapted from Leamy and Saunders (1967). Descriptions of the soil types are given in appendix 1.4.2.



Soil thicknesses vary across the Flat from 20cm up to 1m (Leamy & Saunders, 1967). In the topsoil, these soils have a weak platy structure, and in the subsoil, calcium carbonate accumulation is common (Leamy & Saunders, 1967; Rickard & Cossens, 1968). Rickard and Cossens (1968) identified that the Blackmans – Maungawera soils were saline, although high concentrations of soluble salts in this soil type have only been observed near the Bannockburn Bridge at the southernmost point of the Cromwell Flat.

The soils on the Pisa Range are typically shallow and stony, about 45cm thick, but can range up to 66cm thick and are largely composed of loess (Leamy & Saunders, 1967).

The loess found in the soils found on the Cromwell Flat and the Pisa Range is derived locally from Quaternary glaciations near Wanaka (Leamy & Saunders, 1967).

1.4.3 Climate

Cromwell Flat has a semi arid climate and is one of the driest places in New Zealand. Due to the low precipitation on the Cromwell Flat, it is essentially a barren area that, without irrigation from groundwater and surface water, would be a desert like region (Rickard & Cossens, 1968; Sims, 2009). The summer irrigation season on the Cromwell Flat begins around November and runs until about April/May. Most bore owners drain their bores and switch their pumps off over the winter months to avoid frost damage due to the cold temperatures the area experiences.

Most precipitation on the Cromwell Flat and the Pisa Range is sourced from westerly fronts. These are predominantly west to northwest air masses during the summer months and south west air masses in the winter months (Sims, 2009). Cromwell Flat has an average annual precipitation of 439.6mm for the 30 year period from 1971 to 2000 (NIWA, 2010). Precipitation decreases during the colder winter months to a minimum of 28.9 mm per month and increases over the warmer summer months to a maximum of 48.7 mm per month (NIWA, 2010). Heavy rains are restricted to the warmer months and are sporadic. Snow on the Cromwell Flat is rare with only 7 snow days per annum, but frosts can occur over night throughout any season (Rickard & Cossens, 1968).

Monthly average temperature and precipitation readings for the Cromwell Flat are shown in figure 1.4.

The Pisa Range has a seasonal snowline around 1000 masl, but during the colder winter months can fall to lower elevations (Sims, 2009). During the course of this study, snow fell down to an elevation of 609 masl (10 August 2010). Evaporation on the Cromwell Flat is high, with an annual average of 1430mm based on records using a raised pan over a 20 year period from 1985 to 2005 (NIWA, 2010).

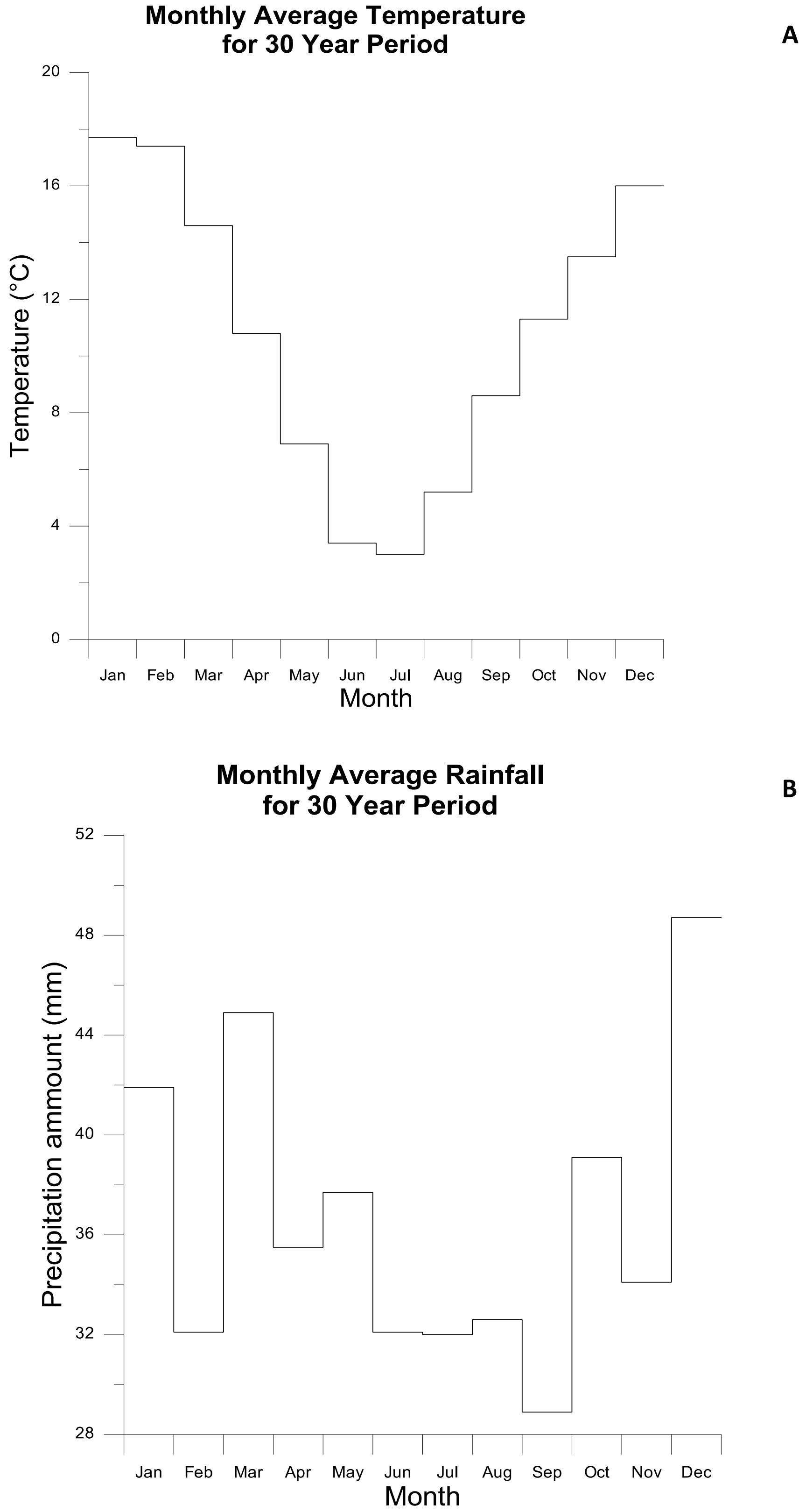


Figure 1.4 – Graphs showing average monthly temperature (A) and precipitation (B) for the Cromwell Flat. Each value for both graphs is monthly average for the 30 year period 1971 - 2000. Data sourced from NIWA (2010) from climate station 'Cromwell 2' (1300288mE, 5006297mN).

Climate data used in this study came from a single climate station remotely monitored by NIWA known as 'Cromwell 2' (NIWA, 2010). The climate data for the climate station 'Cromwell 2' was sourced from Cliflo, an online public database where NIWA shares climate data collected from climate stations throughout New Zealand. Since there are no climate stations at the Cromwell end of the Pisa Range, data from Cromwell 2 was used for the entire Cromwell Flat area and the Pisa Range and foothills.

1.4.4 Vegetation

Vegetation cover of the Cromwell Flat was first documented by Park (1908) and Cockayne (1911). Park (1908) noted that the dominant vegetation cover on the Cromwell Flat was tussock.

Figure 1.5 – Photo of undeveloped terrace surface near McNulty Inlet. Cromwell Flat would have looked like this before development. The light green patches are the sheep plant. Note the Pine trees in the background.

Cockayne later identified two different types of tussock species on the Flat; *Poa Caespitosa* and *Festuca Rubra*. These tussocks occurred around the active sand dunes along the eastern edge of the flat. Cockayne also documented the existence of the Sheep Plant or *Raoulia lutesens*. Leamy and Saunders (1967) also documented these native plants, along with Manuka (*Leptospermum scoparium*), Matagouri (*Discaria toumatou*), and a number of plant weed species.

Presently, the native vegetation cover that both Park (1908), Cockayne (1911) and Leamy and

Saunders (1967) documented is not as dominant as it used to be. Irrigation and agricultural development has resulted in the planting of pastoral grasses, along with fruit trees and grape vines, although native tussocks still exist naturally on the Cromwell Flat in the Chaffer Beetle Colony. Other vegetation cover is made up of Pine tree (*Pinus radiata)* plantations and other introduced tree species used for shade and shelter belts.

On the Pisa Range, the dominant vegetation cover is pastoral grasses, tussock, Matagouri (*Discaria toumatou*) and other introduced plants such as Rose Hip bushes (*Rosa canina*).

Figure 1.6 – Photo looking east across the Cromwell Flat from the Pisa Range showing Development of land and vegetation cover.

1.5 Water Development and Land Use

Land use of the Cromwell Flat has changed throughout the years. Before any water development was carried out, land use of Cromwell Flat was restricted due to the arid environment and the Cromwell Sands. It is possible that the Cromwell Flat was used for grazing of sheep, but vegetation in the early days would have been limited. Water development and land use increased with the discovery of gold in Central Otago and the township of Cromwell being established in 1862 (Statistics New Zealand, 2006; Turnbull & Forsyth, 1988). Park (1908) produced a map of the Cromwell sands which shows a water race diverting water from somewhere near the back of the Flat to a dam on the edge of the township. This is likely to be some of the first water development on the Cromwell Flat as most of the residential and gold mining areas were located close to the Clutha and Kawarau Rivers. The location of this water race and reservoir that Park (1908) documented is shown in figure 1.7.

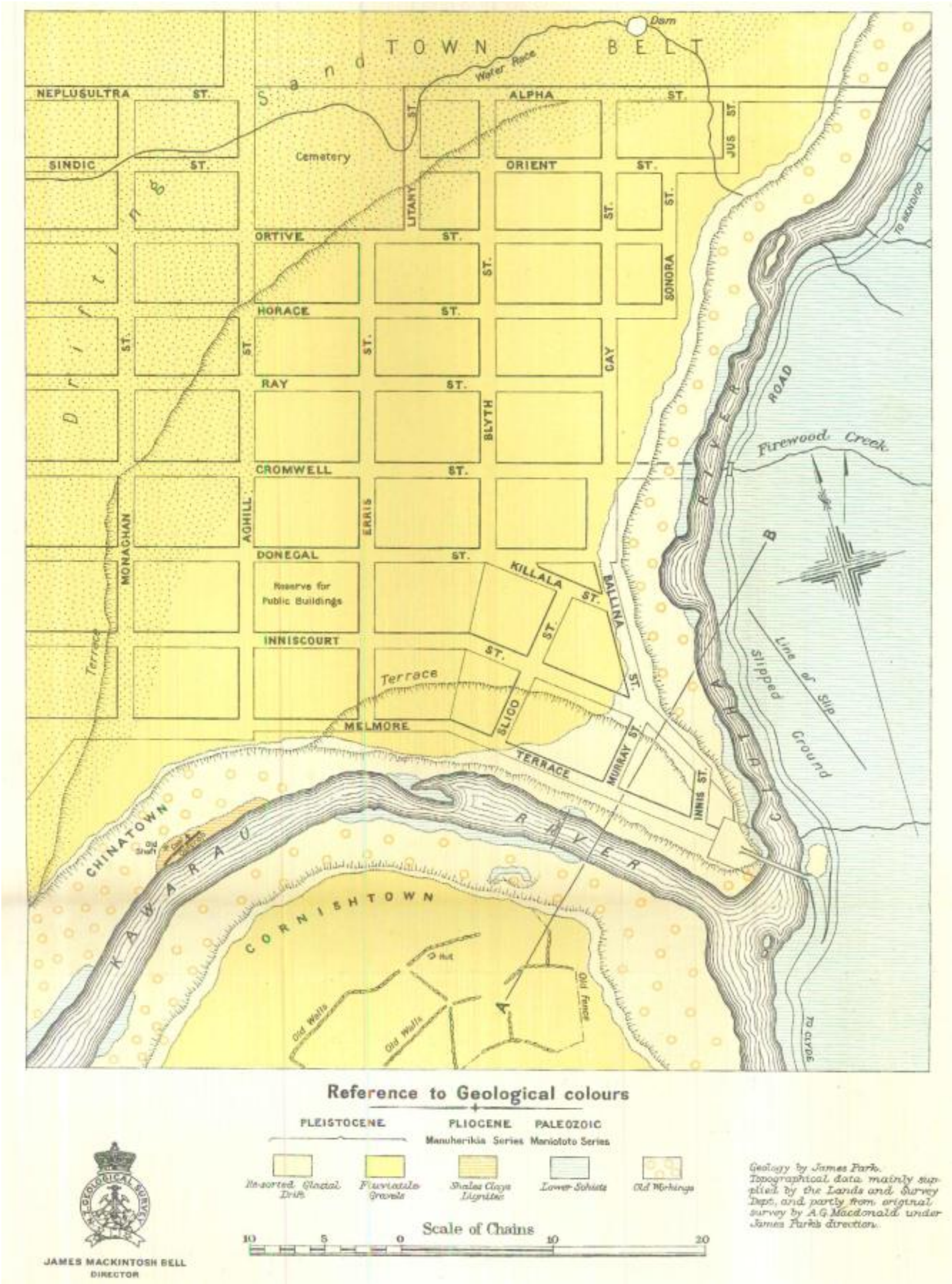


Figure 1.7 - Early map of Cromwell Township and the confluence of the Kawarau and Clutha Rivers showing water race and reservoir at top of map (from Park, 1908). The stippled pattern represents the Cromwell sands, the dark yellow colour is Quaternary sediments, the light yellow with circles are Tertiary sediments and the blue striped pattern is the Otago Schist.

Figure 1.8 – Photographs of a modern bore set below the ground surface (top), a converted 2m diameter mine shaft well (middle) and an older bore housed in pump shed (bottom).

The first wells that were developed on the Cromwell Flat were originally used as mine shafts to extract gold from the Quaternary alluvium in the late 1800’s to the early 1900’s (Graham Stewart, pers comm, 2010). These large, 1 – 2 m diameter, wells were later converted for groundwater extraction with the development of land for vineyards and orchards. These wells are lined with large steel casings to stop them collapsing. One of these wells is shown in the middle photo of figure 1.8. The first modern bores were put down in the late 1970’s and early 1980’s as the area began to be developed for lifestyle blocks, vineyards and orchards. These bores have diameters ranging from 100mm to 500mm, are steel lined to stop the bore collapsing and typically have a slotted PVC section of pipe at the base of the bore (Graham Stewart, pers comm, 2010; O.R.C., 2010a). Modern bores are typically placed approximately a meter below ground level in a concrete lined box to provide insulation and stop water freezing in pipes during winter. Older bores are housed in pump sheds at surface (figure1.8).

Extraction rates are typically <45 L/s, although the Cromwell Town Supply bore can extract groundwater up to a rate of 210 L/s (O.R.C., 2010a).

As of February 2010, there are 66 documented bores and wells across the Cromwell Flat but not all are currently used (O.R.C., 2010a). Figure 1.9 shows the distribution of all groundwater bores across the Cromwell Flat.

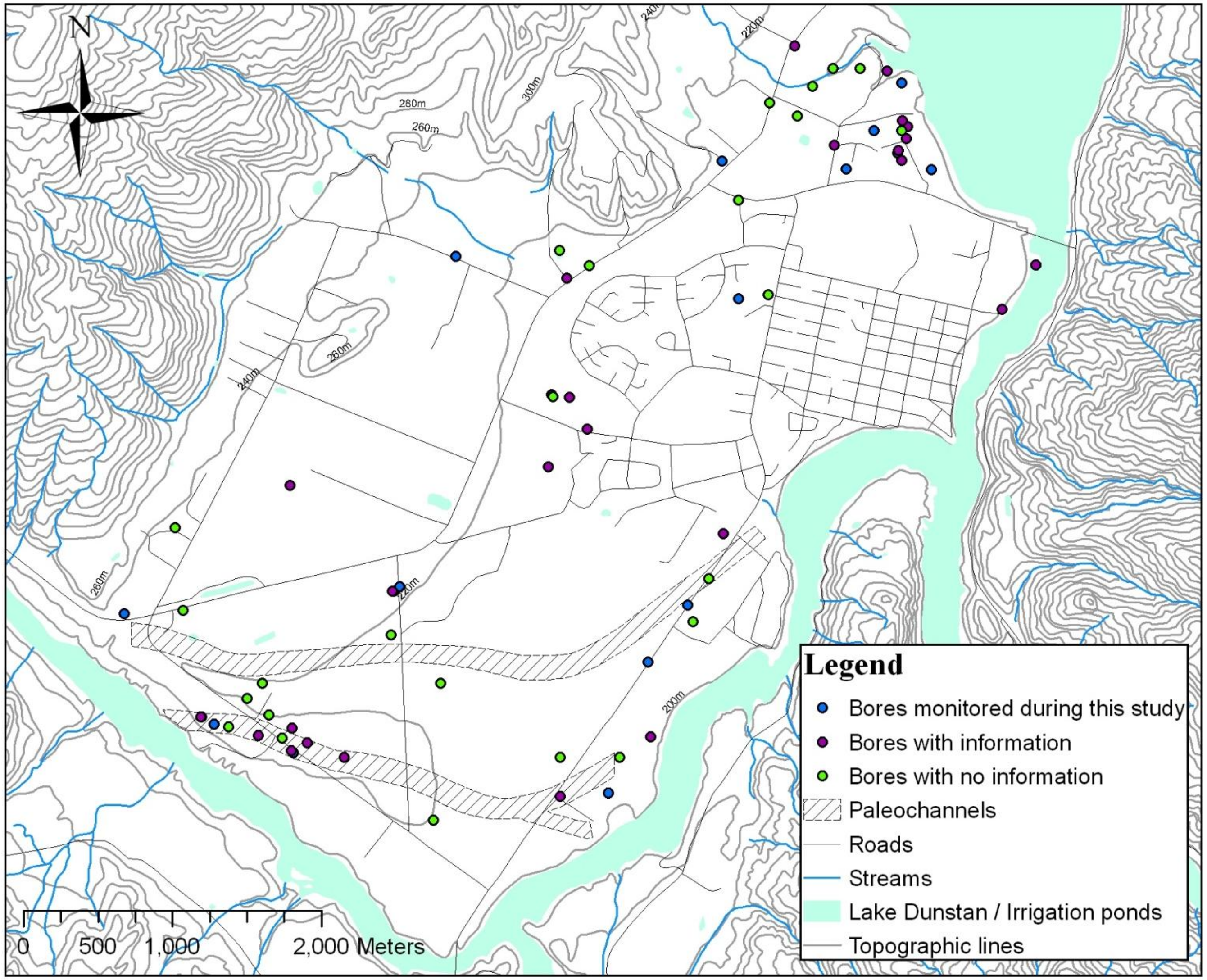
Other water resources used on the Cromwell Flat are private surface water extractions from Lake Dunstan and the private Ripponvale Irrigation Scheme (Murphy & O.R.C., 2009). The Ripponvale Irrigation Scheme extracts approximately 16 Mm^3/yr of water from the Kawarau Arm of Lake Dunstan, and is distributed across the Flat via a network of water races and pipes. It is used for both irrigation and domestic purposes (Murphy & O.R.C., 2009).

1.6 Previous Work

Some of the earliest work carried out in the Cromwell region was by Park (1908). Park carried out a general geologic survey of the Cromwell Flat and neighbouring areas. In his work, he discussed the possibility of artesian aquifers beneath the Cromwell flat. Park (1908) also noted that with irrigation, the Cromwell Flat had the potential to be cultivated. Some of Park’s maps show water races and dams that were diverted across the Flat (figure 1.7) presumably as a water supply for the township. The source that supplied the water race is not shown.

Geophysical investigations in the late 1930’s identified 2 major buried paleochannels (displayed in figure 1.9) of the Kawarau River at the southern end of the Cromwell Flat (Modriniak & Marsden,

Figure 1.9 – Map showing location of bores from the O.R.C. database (2010a) for groundwater bores for the Cromwell Flat. Bores with no information in the O.R.C. database either had no contact details or were no longer used. The paleochannels are also shown.



1938). These investigations were initially used to find buried channels where alluvial gold would be concentrated, but later proved to be valuable for helping establish well and bore sites for groundwater extraction (Graham Stewart, pers comm, 2010).

Soil surveys were carried out across Cromwell Flat during the 1960's (Leamy & Saunders, 1967; Rickard & Cossens, 1968), and looked at the soil types and the viability of land development through irrigation for agricultural use.

During the late 1970's and early 1980's interest in the Clyde Dam Hydroelectric development began and a number of investigations into the potential geologic and hydrogeologic resources of the Upper Clutha Valley were carried out. The most relevant investigations for this study were by Close and McCallion (1988), who looked at the groundwater chemistry of a number of wells throughout the Upper Clutha Valley including Cromwell Flat. Their investigations were implemented to determine the main chemical constituents of groundwater in the area and try and predict the impacts of Lake Dunstan on the quality of the groundwater resource.

With the filling of Lake Dunstan in the early 1990's, the O.R.C. completed a chemical analysis of groundwater from selected bores across the Cromwell Flat and currently monitor groundwater depth in 2 bores remotely. A number of pump tests on private bores have been carried out to determine and test groundwater extraction flow rates. These have been documented in number of private reports, although not many of them were helpful for this study as they didn't provide enough information to accurately assess the hydrological properties of the CTA (MWH NZ Ltd, 2007).

1.7 Research Methods

A literature review and desktop study of the Cromwell Flat area was conducted initially to get a better understanding of the area and determine where knowledge was lacking.

To identify bores and landowners so land access could be permitted, a database held by the O.R.C. containing information for all known bores and wells across the Cromwell Flat was used. This database included information on bore owners, contact details, bore location, bore logs and water chemistry data. The O.R.C. database listed 66 bores across the Cromwell Flat, but only 41 bores from the database had enough information to be useful for this study. Figure 1.9 shows the locations of bores with useful information and bores without any information used in this study.

Due to the nature of Cromwell as holiday area, many land owners were unable to be contacted as they lived out of town or no contact details were given in the O.R.C. database. The bores that had no contact details were registered under a private trust name so access to these bores could not be arranged. Some of the bores had been abandoned after drilling due to being dry, or were no longer used. As a consequence, only 17 out of the possible 41 bores in the O.R.C. database could be accessed to monitor depth to groundwater and be sampled for stable isotopic analysis. The 17 bores used for monitoring groundwater levels and sampling are shown in figure 1.9 as bores that were monitored during this study.

Sample site and bore collar locations along with elevations were determined using the O.R.C. database and a Garmin GPSMap 60. Elevations were surveyed to an accuracy of <5m by calibrating the GPS to a known elevation within the field area. Units for elevation measurements are in metres above sea level (masl). All coordinates are in New Zealand Transverse Mercator Projection 2000.

Depth to groundwater measurements were carried out using a portable water level indicator with measurements being carried out quarterly. Each visit to take measurements coincided approximately with each season of the year. The first field visit to monitor groundwater levels began in May 2010 and ended in February 2011, with each visit spaced approximately every three months. Stream flow measurements of the Pisa Range streams were taken to help determine inflows and outflows to the CTA. Stream flow measurements were collected when access to streams was made available by landowners.

The information collected from the literature review was used to create geologic maps, geomorphic maps, structure contour maps and hydrogeological cross sections. Depth to groundwater data collected during the course of this study were used to create four water level contour maps of the CTA for each season of the year.

The O.R.C. database of chemical constituents for selected Cromwell Flat groundwater bores were analyzed to establish groundwater chemistry and any chemical patterns or variations in the CTA. The methods of chemical analysis used were piper and stiff diagrams along with water quality. The water chemistry of the CTA was then compared with the water chemistry of Lake Dunstan, the tributaries of Lake Dunstan and other local groundwater basins (Wanaka basin and the Wakatipu basin) to determine the regional context of the CTA.

A total of 17 water samples collected by the O.R.C. were used in this study for chemical analysis. 5 water samples from Lake Dunstan and its tributaries were collected with 1 sample collected in July 1996, 1 in August 1996 and 3 in December 2003. A total of 12 bores and wells were sampled with 3 samples collected in November 1998, 1 sample in September 2006 and 8 in December 2003.

Sampling of water for stable isotopic analysis was carried out across 3 trips during April, May, and August 2010 as a part of this study. Samples were collected from Lake Dunstan, Pisa Range streams, snowfall on Pisa Range, rainfall, water canals and groundwater bores. A total of 50 samples were collected; 10 Lake, 7 stream, 9 snowfall, 3 rainfall, 4 water race and 17 groundwater bore locations. The stable isotopic data were used to determine any isotopic signatures in the different water sources around the Cromwell Flat so recharge and discharge sources of the CTA could be identified, and any interactions between the aquifer and Lake Dunstan could be observed.

Finally, using the information collected during this study, a water balance and conceptual hydrogeological model were constructed to provide an estimate for allocating groundwater from the CTA.

1.8 Thesis Format

This thesis is presented in 6 chapters. Chapter 2 describes the geology, geomorphology and the Quaternary deposits that make up the CTA along with structural, depositional and post – depositional features that impact the CTA. Chapter 3 discusses the surface hydrology of the Cromwell Flat and the hydrogeology of the CTA, including the physical parameters of the aquifer and groundwater flow directions. Chapter 4 discusses the groundwater chemistry of Lake Dunstan and the CTA, and uses stable isotopic analysis to determine the isotopic signature of the water sources in the Cromwell Flat area, recharge sources and interactions with Lake Dunstan. Chapter 5 discusses the source of recharge for the CTA and a water balance is produced to provide an estimate for groundwater allocation. A summary of data and findings from Chapter 2 through to Chapter 5 is given in Chapter 6.

Chapter Two

Geology and Geomorphology

2.1 Introduction

In this chapter, the geology and geomorphology of the Cromwell Flat is described. The basement geology along with regional tectonic setting is discussed in the first section. A brief history of the Tertiary sediments is given including a description of the units, the structural history and development of the buried paleochannels incised into the tertiary sediments. Depositional histories, ages and descriptions of the Quaternary gravels which act as the water bearing unit are included near the end of the chapter.

2.2 Regional Tectonic Setting

New Zealand is situated on the Indo – Australian and Pacific plate boundary. Plate motion is obliquely convergent and has resulted in an east – west subduction regime on the east coast of the North Island and a west – east subduction regime at the south western tip of the South Island (Williams, 1991; Turnbull, 2000). These two subduction regimes are linked via the Alpine Fault which displays dextral strike slip motion with some vertical offset. In the south west of New Zealand, plate movement is dominated by a transform zone with plate convergence rates of up to 45mm/a near the southern tip of Fiordland (Williams, 1991).

Since forming in the Cenozoic, movement along the Alpine Fault has resulted in overriding and buckling of the Indo – Australian and Pacific plates causing uplift at rate of about 10 mm/a. This has led to the formation of the Southern Alps and the erosion of at least 70 km of Pacific Plate (Le Masurier & Landis, 1996; Turnbull, 2000).

The resultant buckling has caused regional scale folding and faulting of the Otago Schist, which has formed the basin and range style landscape (figure2.2) that dominates the Central Otago region (Beanland & Berryman, 1989). These basin and ranges are controlled via northeast trending faulting and folding.

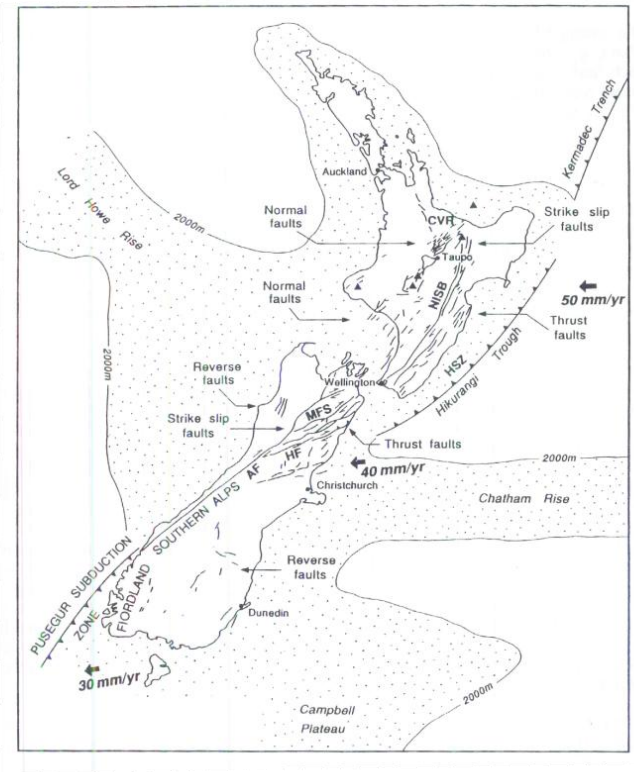


Figure 2.1 – New Zealand plate tectonic boundary (Cowan, 1994)

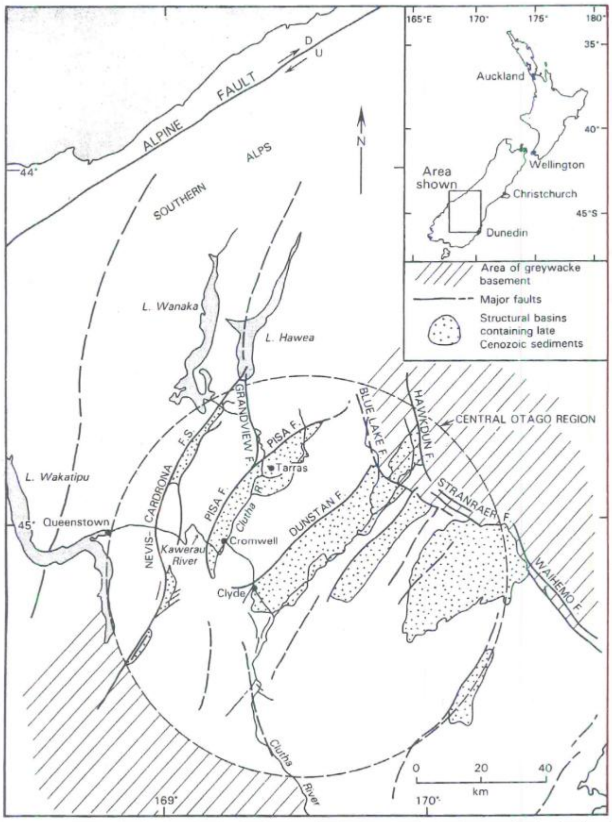


Figure 2.2 – Cromwell-Tarras structural basin and the adjacent basin and ranges of Central Otago. (From Beanland and Berryman, 1989)

The basins are synforms that are linked together via antiforms, which make up the ranges (Turnbull et al., 1992). North east trending faults separate the folds and control the east facing slopes of the structural basins (Turnbull, 2000).

The Cromwell – Tarras Basin, in which the Cromwell Terrace is located, is one such basin (Beanland & Berryman, 1989). The Cromwell – Tarras Basin is displayed in figure 2.2.

2.3 Geology of the Cromwell Flat

The Cromwell - Tarras Basin is surrounded by Rakaia Terrane Otago Schist, which provides the basement of the basin. The Pisa Range Mountains and the Dunstan Mountains that surround the basin have been stripped of any covering sediments by glacial action and erosion (Beanland & Berryman, 1989; Turnbull, 2000). The valley in between the two mountain ranges has been in filled by younger Tertiary lake and fluvial sediments, and Quaternary glacial sediments (Beanland & Berryman, 1989; Turnbull, 2000). The Pisa – Grandview fault follows the base of the Pisa Range along the western side of the Cromwell – Tarras Basin (figure 2.2). This fault controls deformation beneath the younger sediments out in the basin (Beanland & Berryman, 1989). The surface of the Cromwell Flat is the remnants of glacial outwash terraces from both the Upper Clutha valley and the Kawarau River catchment. Holocene alluvial sediments exist in areas where there are active fluvial processes, although these are limited as currently the only active streams are on the flanks of the Pisa Range (Turnbull, 2000). A geologic map of the Cromwell Flat area, along with a stratigraphic column, is presented in appendix 2.3.

2.3.1 Rakaia Terrane Otago Schist

The Rakaia Terrane, more commonly referred to as greywacke, is of Permian to early Triassic in age, and is composed of interbedded layers of sandstone and argillite deposited in deep marine environment in a subduction setting (Turnbull, 2000). Part of the Rakaia Terrane experienced metamorphism in the Jurassic and early Cretaceous during the Rangitata Orogeny (150 – 200 Ma). In Otago, the metamorphosed section of the Rakaia Terrane is referred to as the Otago Schist (Turnbull & Forsyth, 1988; McSaveney et al., 1992). The folding and faulting that accompanies the Otago Schist is thought to have been initiated during Rangitata Orogeny as well (Turnbull & Forsyth, 1988; McSaveney, et al., 1992). The Otago Schist displays a range of different grades of metamorphism and textural zones but is mainly made up of quartzo – feldspathic metagreywacke and meta – argillite with some bands of greenschist (Wood, 1978; Turnbull, 2000).

2.3.2 Tertiary Sediments

Most of the synform basin valleys of Central Otago contain Tertiary lacustrine and fluvial sediments that rest unconformably on the Waipounamu Erosion surface of the Otago Schist (Turnbull, 2000).

These lacustrine and fluvial sediments are part of the Manuherikia Group and are late Miocene to early Pliocene in age (Douglas, 1986; Turnbull, 2000). During this period, a large inland, freshwater lake environment formed with associated fluvial environments developing around the lake margins (Douglas, 1986; Turnbull, 2000).This lake, known as Lake Manuherikia, deposited sediments consisting of interbedded clays, silts, quartz sandstones and conglomerates. Silica cementation of the sandstones and conglomerates is common in the Cromwell region.

Conformably overlying the Manuherikia Group sediments in the Cromwell – Tarras basin are the Hawkdun Group sediments which contains the Maniototo Conglomerate (previously known as the Maori Bottom Group) (Youngson et al., 1998). The Hawkdun Group sediments are of late Miocene to Pliocene age, and represent the onset of the currently active tectonic regime in Otago. They also represent the change in depositional setting from a fresh lake to a fluvial plain environment (Beanland & Berryman, 1989; Turnbull, 2000). The Maniototo Conglomerates are derived from the uplift of the greywacke and schist mountains around the Waihemo, Stranraer, and Hawkdun faults, and also contain some reworked Manuherikia Group sediment (Bishop, 1974).

Both the Manuherikia Group and the Hawkdun Group sediments once covered most of Central Otago, but subsequent uplift of the mountain ranges in Central Otago during the Kaikoura Orogeny and erosion from glaciation has confined most of these sediments to the valleys (Beanland & Berryman, 1989; McSaveney et al., 1992; Turnbull, 2000).

2.3.3 Quaternary Sediments

The Quaternary sediments around the Cromwell Flat are all Pleistocene glacial outwash gravels from the Lowburn advance, Lindis advance, Luggate advance and the Lindis advance. The Luggate outwash gravels also contain some penecontemporaneous fan derived alluvium. These deposits overlie the Tertiary deposits unconformably (Turnbull, 2000). The glacial outwash gravels are related to six glacial advances at the top of the Upper Clutha Valley. Only some deposits have been dated in the laboratory, so most of the ages assigned to each advance and associated deposits have been correlated from other deposits in the area.

This has resulted in some discrepancy of the ages of the deposits in the literature. Dates that been assigned for these periods of glaciation and deposition of gravels are shown in table 2.1.

Glacial Advance	Glacial Stage/Stadial (Beanland & Berryman, 1989)	McKellar (1960) ages	Officers of the Geological survey (1984) ages	Beanland & Berryman (1989) ages	McSaveney et al. (1992) ages	Turnbull (2000) ages.	Thompson Pers comm. (2010) ages
Northburn	1st Stage	-	500 ka	500 ka	1 Ma - 620 ka	Early Quaternary	-
Lowburn	2nd Stage	-	250 ka	250 ka	404 +150/- 60 ka[2]	Max. range 620 – 660 ka Min. range 300 – 530 ka	300 ka
Lindis	3rd Stage	-	140 ka	140 ka	413 +∞ /-85 ka[3]	413 +∞ /-85 ka[3]	-
Luggate	4th Stage, 1st Stadial	-	70 ka	70 ka	-	127 ka	140 ka
Albert Town	4th Stage, 2nd Stadial	-	35 ka	50 – 35 ka	-	65 ka	85 ka
Hawea/Mt Iron	4th Stage, 3rd Stadial	15.0 +/- 0.2 ka[1]	18 – 16 ka	23 – 16 ka	15.1 +/- 0.2 ka[4]	15.1 +/- 0.2 ka[4]	-

Table 2.1 – Table showing assigned ages for each glacial advance in the Upper Clutha Valley. All ages are assigned by correlation with other glacial advances of known age unless noted. [1] C^{14} dating of organic material from peat immediately above Hawea outwash gravel, [2] dating of Travertine cement from Lowburn outwash gravels, [3] U – Th dating of a concretion from Lindis lake deposits, although Th may have been contaminated by silts in the deposit, [4] Age taken from McKellar.

None of the glacial advances reached the Cromwell Flat with the largest and oldest advance only reaching Northburn, some 15 km up valley from Cromwell (McSaveney et al., 1992). However the outwash terraces from nearly all of the glacial advances can be identified around the Cromwell Flat.

The outwash deposits of most importance for this study are the Luggate and Albert town outwash gravels along with the contemporaneous alluvial fan deposits, as they form the CTA.

2.3.4 Luggate and Albert Town Gravels

The Luggate outwash gravels are described by Turnbull (2000) as being slightly weathered to moderately weathered gravels. The Albert Town outwash gravels are unweathered to weakly weathered gravels (Turnbull, 2000). Both outwash gravel units have similar lithologic descriptions typically being sub –rounded to rounded, sandy gravel to cobbly sandy gravel with some silt. Boulders and sand rich layers are common throughout both units. The grain size of these gravels tends to decrease down valley (Thomson, 2002; O.R.C., 2010a). Both outwash gravel units are moderately to poorly sorted and are coarsely stratified locally (Officers of the New Zealand Geological Survey, 1984).

Both the Luggate and Albert Town gravels are made up of schist and greywacke, and dip at a shallow angle toward the east (Thomson, 2002; O.R.C., 2010a). The Luggate outwash gravel unit has contemporaneous fan alluvium deposits that fan out from gullies at the base of the Pisa range (Turnbull, 1988; Turnbull, 2000). The Albert Town outwash gravel also has some minor contemporaneous fan alluvium deposits along with some more recent Holocene alluvial gravels up Burn Cottage valley at the northern end of the of the Cromwell Flat (Turnbull, 1988; Turnbull, 2000).

These contemporaneous fan gravels are typically composed of poorly sorted, sub angular to sub rounded cobble with some finer material. Deposits are poorly stratified (Officers of the New Zealand Geological Survey, 1984).

The boundary between the Luggate and Albert Town gravels is a prominent terrace riser which cuts roughly across the middle of Flat in a north east – south west direction. At the south west end it curves around sharply toward the west.

Both the Luggate outwash gravels and the Albert Town outwash gravels have small localised lenses of calcium carbonate and it is common for clasts to have thin coatings of lime on their surfaces (Thomson, 2002). Calcium carbonate build up occurs at depths of roughly 2 m below the surface and is thought to have precipitated out from surface water leaching calcium carbonate out of the loess in the soils above (Thomson, 2002). The basement Otago Schist contains calcite as an accessory mineral and has been suggested as the source of any calcium carbonate in the alluvium of the Wanaka Basin and the Wakatipu Basin (Coombs et al., 1985; Rosen et al., 1997).

A complicating factor for the Luggate and Albert Town glacial outwash deposits is the location of the Cromwell Flat at the confluence of the Clutha and Kawarau Rivers. Along with glacial geomorphic features in the Wakatipu Basin, evidence of glaciation and outwash gravels are found along the Kawarau Gorge (Bell, 1991). Ages of the glaciations in the Wakatipu Basin and Kawarau Gorge are of similar age to the glaciations in the Upper Clutha Valley. This indicates that while the Clutha River was depositing outwash gravels on the Cromwell Flat from glaciations in the Upper Clutha Valley, the Kawarau River would have been transporting and depositing glacial outwash gravels on the Cromwell Flat from the equivalent glaciations in the Wakatipu Basin as well (Royden Thomson, pers comm, 2010).This would cause the glacial outwash deposits from the two different sources to interfinger.

2.3.5 Holocene Gravels

The most recent deposits on the Cromwell Flat are alluvial and fluvial gravels associated with the gullies and active streams at the base of the Pisa Range (Turnbull, 2000). The most prominent of these deposits are the Riches gully stream and the Burn Cottage Rd. Stream. Both of these deposits are largely localised at the Base of the Pisa Range with the Riches gully stream not flowing much further than the transition from hillside to the Flat (Turnbull, 2000). The gravels in the Burn Cottage Rd. valley are concentrated in the valley and don't spread much further than the mouth of the valley (Turnbull, 2000).

2.4 Structure of the Cromwell – Tarras Basin

The structure of the Cromwell Flat is controlled by regional faulting and folding of the Otago Schist. The Pisa Range to the west of the Cromwell – Tarras Basin and the Dunstan Mountains to the east both display large scale antiforms in the foliation of the Otago Schist (Beanland & Berryman, 1989; Turnbull, 2000). These antiforms are block faulted mountains that are asymmetric in cross section and have steep scarps on the southeast limbs, and gentle sloping limbs on the northwestern sides (Officers of the New Zealand Geological Survey, 1984; Beanland & Berryman, 1989; Turnbull, 2000). The depression that lies between the two block faulted mountains is the down faulted Cromwell - Tarras basin. This basin is comprised of a synform related to the antiforms on either side of it. The basin extends up the valley and is covered by approximately 1000 m of Tertiary and Quaternary sediments (Officers of the New Zealand Geological Survey, 1984; Turnbull, 2000).

This folding is the result of crustal shortening, as deformation from the ongoing Kaikoura Orogeny

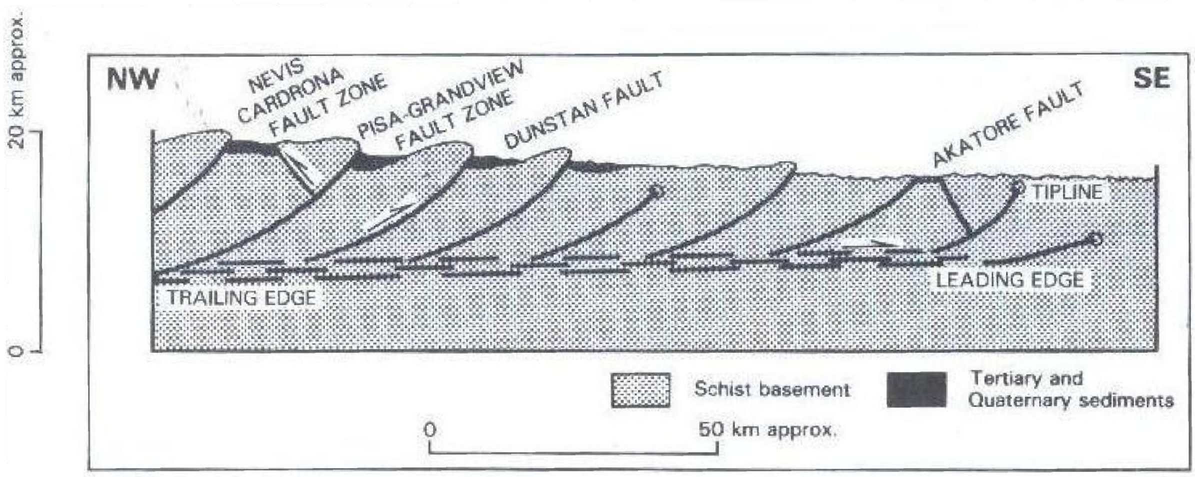


Figure 2.3 – Schematic showing the possible decollement linking the major faults of the Central Otago region at depth. (from Beanland and Berryman, 1989)

has produced uplift throughout Central Otago and much of New Zealand (Beanland & Berryman, 1989; Turnbull, 2000). Along the bases of the block faulted mountains there are large scale faults that trend northeast – southwest. These faults are thought to be connected at depth via a regional crustal decollement in the Otago Schist (Beanland & Berryman, 1989). The Pisa Fault is one such fault and traces the south eastern foot of the Pisa Range in the Cromwell – Tarras Basin. The Pisa Fault is reverse fault and consists of a zone of deformation that is up to 500 m wide made of crushed and intensely sheared schist with seams of clay gouge that are sub parallel to schistosity (Officers of the New Zealand Geological Survey, 1984).

The Tertiary sediments, under the Cromwell Flat, have also been folded next to the Pisa fault zone into an asymmetric synform. The Tertiary sediments at the western side of the basin dip steeply to the northwest, forming an over turned limb (figure 2.4). On the southeast side of the basin, the Tertiary sediments dip gently toward the northwest around 15 – 20° (Officers of the New Zealand Geological Survey, 1984). The axis of the synform lies about 1km basin ward of the Pisa Range (Officers of the New Zealand Geological Survey, 1984).

The Quaternary sediments that unconformably overlie the Tertiary sediments have been deformed by movement on the Pisa Fault north of the Cromwell Flat, but there is no evidence to suggest deformation of the Quaternary sediments around the Cromwell Flat area (Officers of the New Zealand Geological Survey, 1984; Beanland & Berryman, 1989). The outwash gravels and alluvial fans that make up the Cromwell Flat have essentially remained undisturbed since deposition. The lack of deformation in the Quaternary sediments, suggests that there has been no further deformation in the under lying Tertiary sediments.

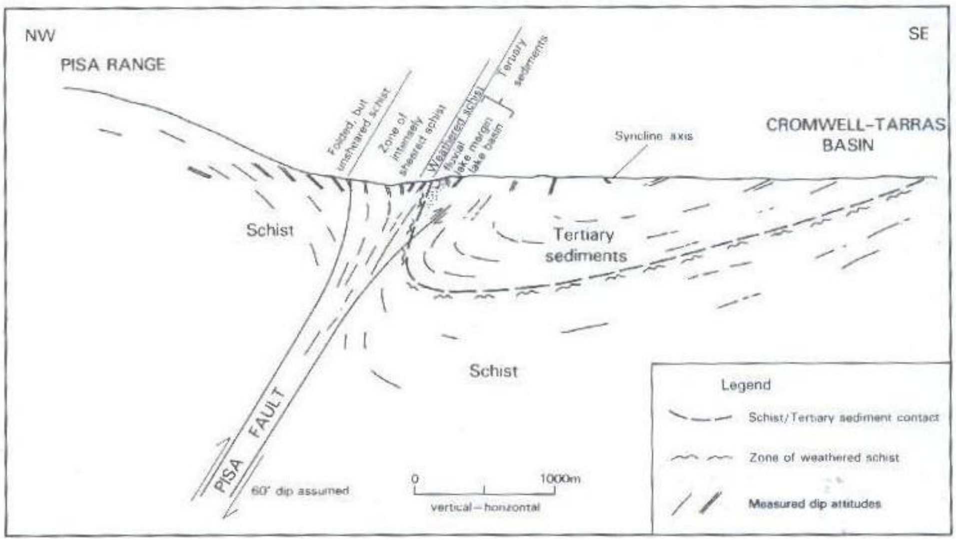


Figure 2.4 – Cross section of the Cromwell – Tarras Basin showing the asymmetric synform structure of the basin (from Beanland and Berryman, 1989).

2.5 Geomorphology of the Cromwell Flat

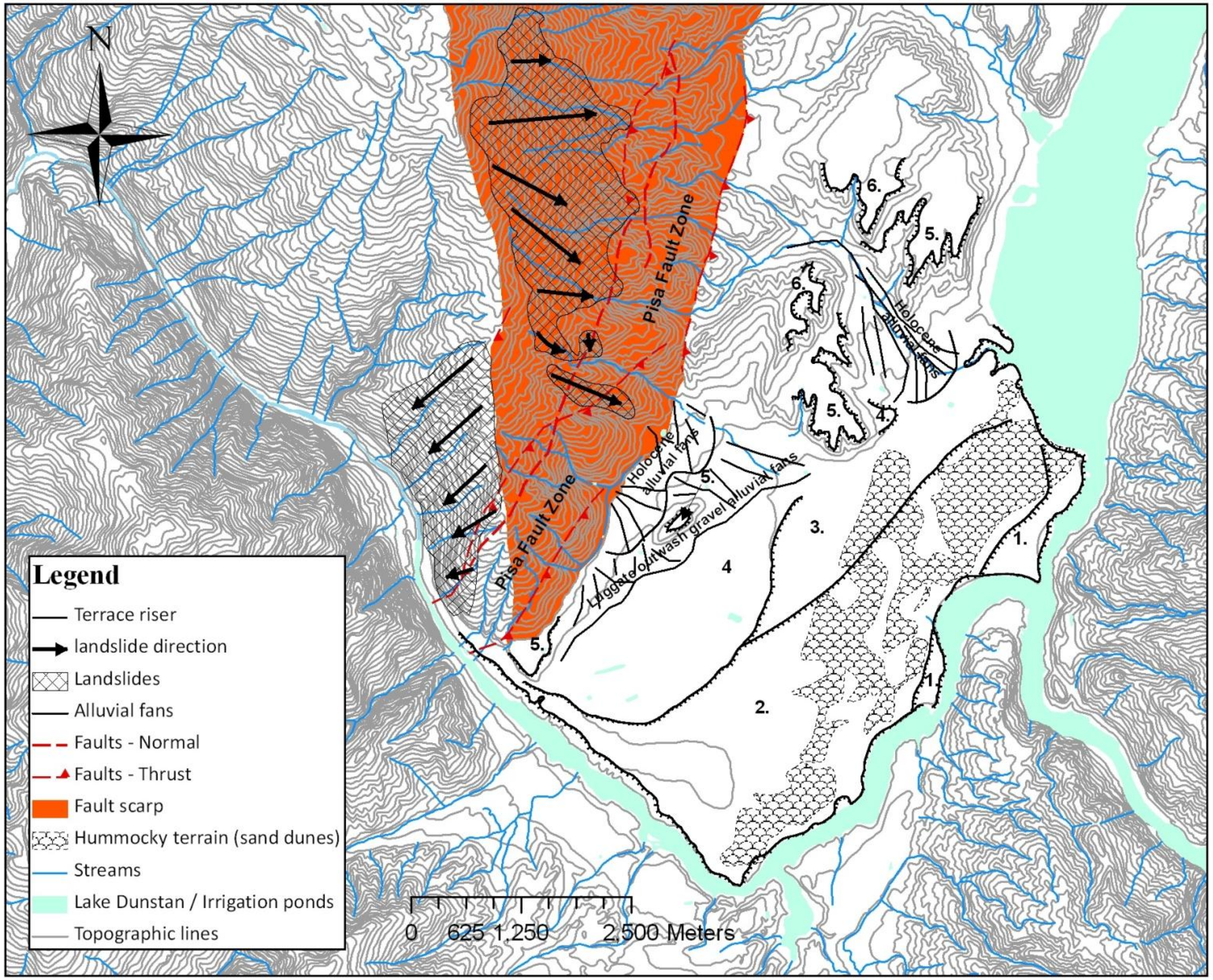
The Cromwell Flat is a paleo fluvial surface of the Clutha and Kawarau Rivers, and smaller alluvial fan surfaces that spread out from the base of the Pisa Range. A map showing the major geomorphological features is shown in figure 2.5.

The fluvial fan surface of the Cromwell Flat is made up of 6 fluvial terraces that display remnants of surface channels and gravel bars from Clutha and Kawarau Rivers (Royden Thomson, pers comm, 2010). The alluvial terraces present at Cromwell are the result of a number of gradational and degradational phases (Royden Thomson, pers comm, 2010). These terraces are numbered in figure 2.5, with 1 being the youngest set of terraces and 6 being the oldest. Terraces 1, 2 and 3 were formed during the deposition of the Albert Town outwash gravels while terrace 4 would have been formed during the deposition of the Luggate outwash gravels. Terraces 5 and 6 would have been formed during the deposition of the Lindis and Lowburn outwash gravels respectively. Land development and coverage of the Cromwell Sands has reduced the appearance of some of the surface channels on these terraces. The Kawarau River is most likely to have been the dominant control on the formation of the surface, as buried paleochannels of Kawarau River have been identified at depth under the Quaternary deposits of the Cromwell Flat and at Cornish point (Modriniak & Marsden, 1938). These major channels have been incised into the folded Tertiary sediments and in filled by Quaternary gravels.

The alluvial fans at the base of the Pisa Range (northwestern boundary) spread out a short distance on to the fluvial terrace surfaces (Turnbull, 2000). These fans are located at the outlets of 3 small gullies that have been incised into the Pisa Range and were formed roughly at the same time as the Luggate Terrace surface (Turnbull, 1988). Around the active streams there are several small alluvial fans that have developed on top of the older Luggate alluvial fan surfaces at the outlet of Riches Gully and in the Burns Cottage Rd. valley (Turnbull, 1988; Turnbull, 2000).

The top of the Pisa Range displays a rolling landscape of low hills and narrow incised gullies called the Waipounamu Erosion Surface. This surface was gradually carved down and eroded over a period of 50 Ma (Landis & Youngson, 1996; Turnbull, 2000). The Waipounamu Erosion surface extends for thousands of square kilometres throughout the Otago region (Le Masurier & Landis, 1996). This surface is visible on the range tops of Central Otago, but on the range flanks and gorges it has been either been buried by younger sediments or eroded. The south – western flank of the Pisa Range (northwestern boundary of the Cromwell Flat) is one such eroded flank.

Figure 2.5 – Map of the major geomorphological features of the Cromwell Flat (adapted from Turnball, 1988 and Turnball, 2000). The numbers represent terrace surfaces that are the result of a number of aggradational and deggradational phases.



The southwestern flank of the Pisa Range is an eroded fault scarp that dips at an angle of 20° down into the Cromwell – Tarras Basin (Beanland & Berryman, 1989; Turnbull, 2000). The extent of the fault scarp above the Cromwell Flat is shown in figure 2.5. Narrow gullies have been incised into the fault scrap, which funnel surface water and water seepage from bedrock and soil cover down to the Cromwell Flat. On this surface there are a number of large, complex schist landslides on this fault scarp which are largely controlled by the foliation of the schist (Bell, 1991). These large landslides were studied in depth during investigations for the hydroelectric development of the Upper Clutha Valley during the 1970's and 1980's (Bell, 1991; McSaveney et al., 1992). A number of these large landslides are located above the foothills of the Cromwell along with a smaller one in the Snow's stream gully (Bell, 1991; McSaveney et al., 1992).

Other geomorphological features of interest on the Cromwell Flat are the Ripponvale Hill and the hummocky surface of the Cromwell Sands. Aside from Terrace risers, Ripponvale Hill provides the only relief on the Cromwell Flat. Ripponvale Hill is an anomalous mesa of Tertiary sediments that is the result of a number of aggradational and degradational phases during the deposition of the Luggate and Albert Town outwash gravels (Royden Thomson, pers comm, 2010). The Tertiary sediments of Ripponvale Hill outcrops up through the surrounding, younger Luggate and Albert Town outwash gravels and may affect groundwater flow around it as the Tertiary sediments have a much lower permeability than the surrounding gravels (Royden Thomson, pers comm, 2010).

The hummocky surface on the on the south eastern side of the Cromwell Flat is the remnants of sand dunes. These sand dunes were deposited via aeolian processes transporting silt and sand from the Clutha River Valley (Park, 1908; Cockayne, 1911). Subsequent land development has reduced the impact of the sand dunes dramatically, although evidence of the sand dunes is still present on the Albert Town Terrace surfaces at the Cromwell Chafer Beetle Nature reserve (Royden Thomson, pers comm, 2010).

2.6 Influences on the Development of the CTA System

2.6.1 Depositional Influences on Hydrogeology

The movement of groundwater in the CTA is likely to be influenced by depositional structures in the outwash gravels. During the deposition, there would have been a number of evolving braided channels transporting and depositing the outwash gravels across the fluvial plain. This would have formed a network of buried channels and zones of permeable gravels and less permeable silts and sands associated with fluvial processes.

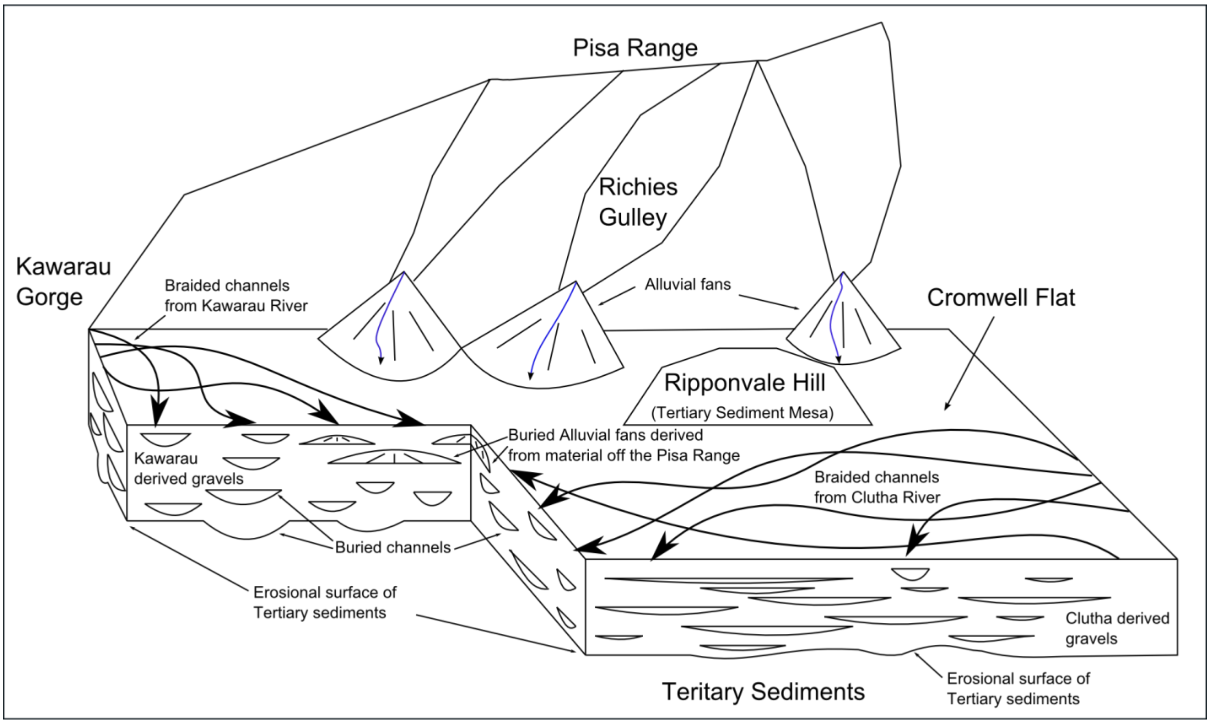


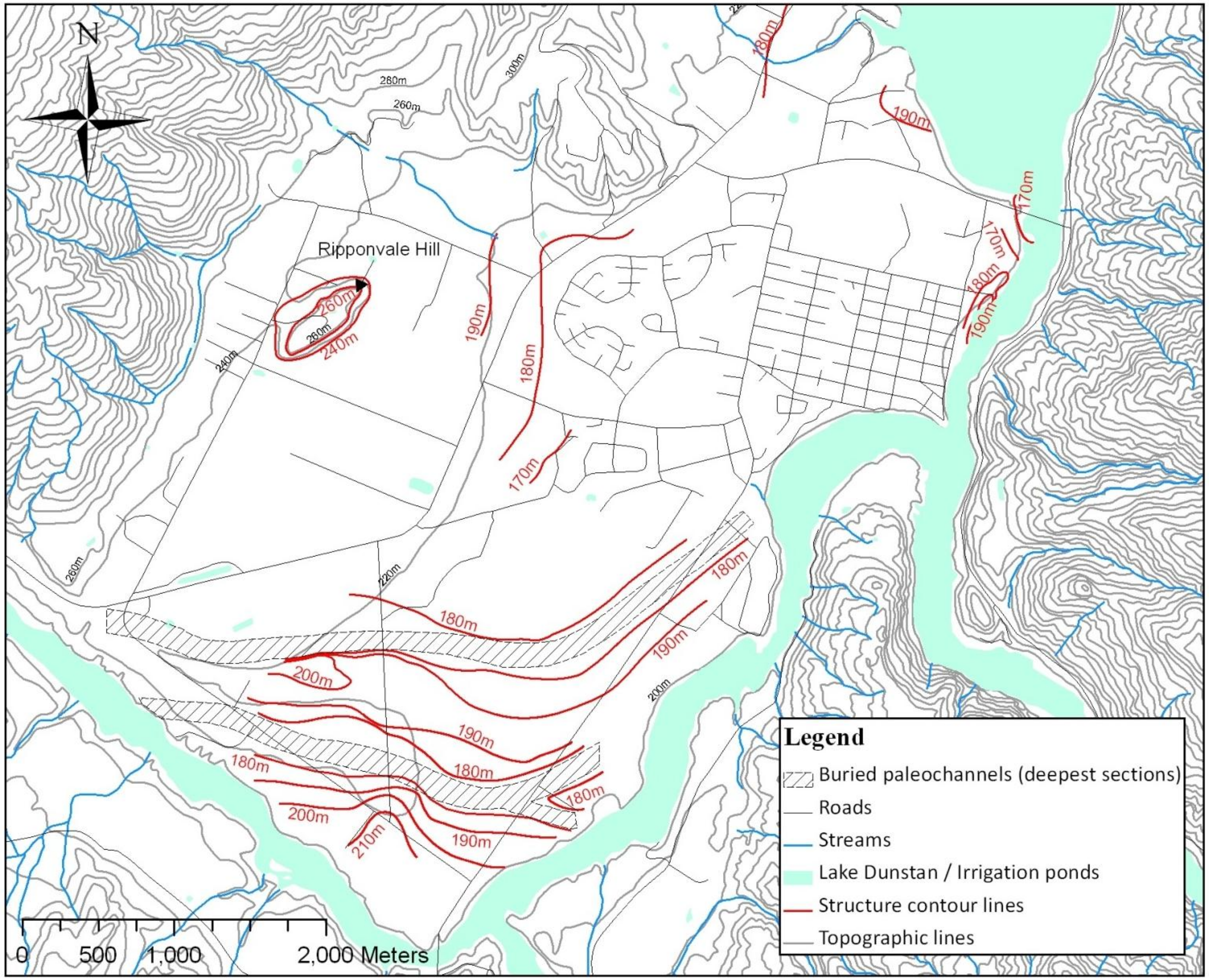
Figure 2.6 – Schematic showing hydrogeologic development of the Cromwell Flat.

These buried channels would act as preferential flow paths for groundwater flow in the aquifer. Grading of the gravels will likely influence the hydrogeology too, as a poorly graded gravel or sand will help to direct groundwater flow (New Zealand Geotechnical Society, 2005). These lenses of poorly graded, fine grained sediment such as sand and silt appear to be relatively small and localized and are associated with the buried channels described above. The size of these lenses ranges from 1 to 3m wide and 0.5 to 1m thick. These lenses of are visible in some of the bore logs and from river and road cuts (Appendix 3.3.1, Figures 2.8 and 2.9).

The biggest depositional influence on the hydrogeology of the CTA is the contact between the less permeable Tertiary sediments and the more permeable Quaternary outwash gravels. The topography of this erosional contact of the Tertiary sediments will control the flow of groundwater through the CTA. A structure contour map of this surface was created using information from Modriniak and Marsden (1938) Graham Stewart from McNeil Drilling (2010) and the O.R.C. database (2010a). This map is displayed in figure 2.7. The eroded surface of the Tertiary sediments is essentially a series of buried valleys and hills. The buried valleys will allow groundwater to flow down them, while the hills or topographic highs will obstruct flow and force groundwater to flow around them.

At the southern end of the Cromwell Flat, there are two major buried paleochannels that are remnants of old flow paths that the Kawarau River would have once taken. These paleochannels are

Figure 2.7 – Map showing structure contours for the eroded surface of the Tertiary sediments (from Modriniak and Marsden, 1938 and the O.R.C. database, 2010a).



roughly west – east orientated and are separated but Tertiary sediment topographic highs. The paleochannels reach depths of about 175 masl, while the topographic highs around the channels are about 200 masl. At the southernmost tip of the Cromwell Flat (Bannockburn Bridge), the Tertiary sediments intersect the surface of the Cromwell Flat. The surface of Tertiary sediments at the northern end of the Cromwell Flat appears to form a wide topographic low that is orientated south – west to north east, and reaches an elevation of about 170 masl. This Topographic low appears to gently slope down on the western side and steepen up on the eastern side. Although information about the Tertiary sediment surface beneath the Cromwell Township is lacking, the asymmetric shape of the Tertiary sediment surface in this part of the Cromwell Flat may suggest erosion along the strike of the folded sediments. This indicates the Tertiary sediment surface at the northern end of the Cromwell Flat has been eroded by the Clutha River.

The major topographic high in the Tertiary sediment surface is Ripponvale Hill. Here the Tertiary sediments outcrop above the surface of the Flat up to an elevation of 260m. Ripponvale Hill will force any groundwater flow to go around it due to the low permeability of the Tertiary sediments. The other known topographical high in the Tertiary sediment surface is known from anecdotal reports to occur at the base of the foothills between the northern edge of the township and just south of Burn Cottage rd (Graham Stewart, pers comm, 2010).

Prior to the filling of Lake Dunstan, groundwater could only be extracted from areas on the Cromwell Flat where the water table was known to be higher than the Tertiary sediment surface. These areas were limited to the buried paleochannels and along the base of the Pisa Range (Graham Stewart, pers comm, 2010). Since the filling of Lake Dunstan, groundwater can now be extracted from areas where groundwater previously didn't exist, although there are still some areas where the water table is still below the Tertiary sediments and no groundwater exists (Graham Stewart, pers comm, 2010). These areas are the Bannockburn Bridge end of the Cromwell Flat and the base of the foothills between the northern edge of the township and just south of Burn Cottage rd (Graham Stewart pers comm. 2010).

2.6.2 Structural Influences on Hydrogeology

There doesn't appear to be many structural influences on the hydrogeology of the CTA due to the relatively young age of the gravels and the most recent seismic activity and sediment deformation on the Pisa Fault being concentrated near the northern end of the Cromwell – Tarras basin (Officers of the New Zealand Geological Survey, 1984; Beanland & Berryman, 1989). At the northern of the Cromwell – Tarras basin, faulting and folding of the Quaternary outwash gravels was observed. This deformation could alter the water table or cause groundwater flow to change direction. Since the deposition of the Quaternary outwash gravels on the Cromwell Flat, no deformation has been observed, suggesting that there has been no seismic activity at the Cromwell end of the Pisa Range fault.

Structural highs in the basement schist have been identified out in Lake Dunstan from drilling (Thomson, 1978). None of these structural highs have been identified beneath the Cromwell Flat.

Groundwater flowing out of fractures in the basement schist at the back of the Cromwell Flat may be influenced by the Pisa Fault shear zone. Clay gouge, associated with shearing, exists throughout the shear zone and would reduce water flow through these fractures into the CTA.

The only other geological structures that may influence the hydrogeology of the CTA are the folded Tertiary sediments beneath the Quaternary outwash gravels, but due to the highly eroded and scoured surface of the Tertiary sediments, any folding or faulting at this surface would have been removed prior or during the deposition of the outwash gravels.

2.6.3 Post Depositional Influences on Hydrogeology

Precipitation of calcium carbonate in the subsoil and in the outwash gravels of the Cromwell Flat is common as calcium carbonate exists naturally in the gravels and soils. Calcium carbonate build up has been documented by Leamy and Saunders (1967), Bell (1991) and Thomson (2002). It is concentrated by the percolation of water down through the soils and gravels from the surface (Leamy & Saunders, 1967; Thomson, 2002). When the calcium carbonate precipitates out, it forms less permeable zones around clasts in the gravel. These zones have the potential link to together and form a less permeable layer or “pan” in the gravels which will affect groundwater flow. Thomson (2002) investigated the potential for the existence of a pan in the shallow subsurface at the southern end of the Flat.

The findings from this investigation found that many of the clasts in the gravel had a thin layer of calcium carbonate on them, but no pan or concentrated calcium carbonate layer was evident.

However, in exposures of the outwash gravels in Kawarau Arm (figure 2.8), a thin band about 10 – 20mm thick, of calcium carbonate cemented coarse sand was visible. This band was moderately indurated and had a lower permeability than the uncemented sediments around it. This layer was about 10m below the surface of the Flat and was the only one visible at the location, although the majority of the gravels at this site were loosely cemented together by calcium carbonate. Loose boulders from the outcrop also had thick coatings of white calcium carbonate with smaller clasts cemented to it.

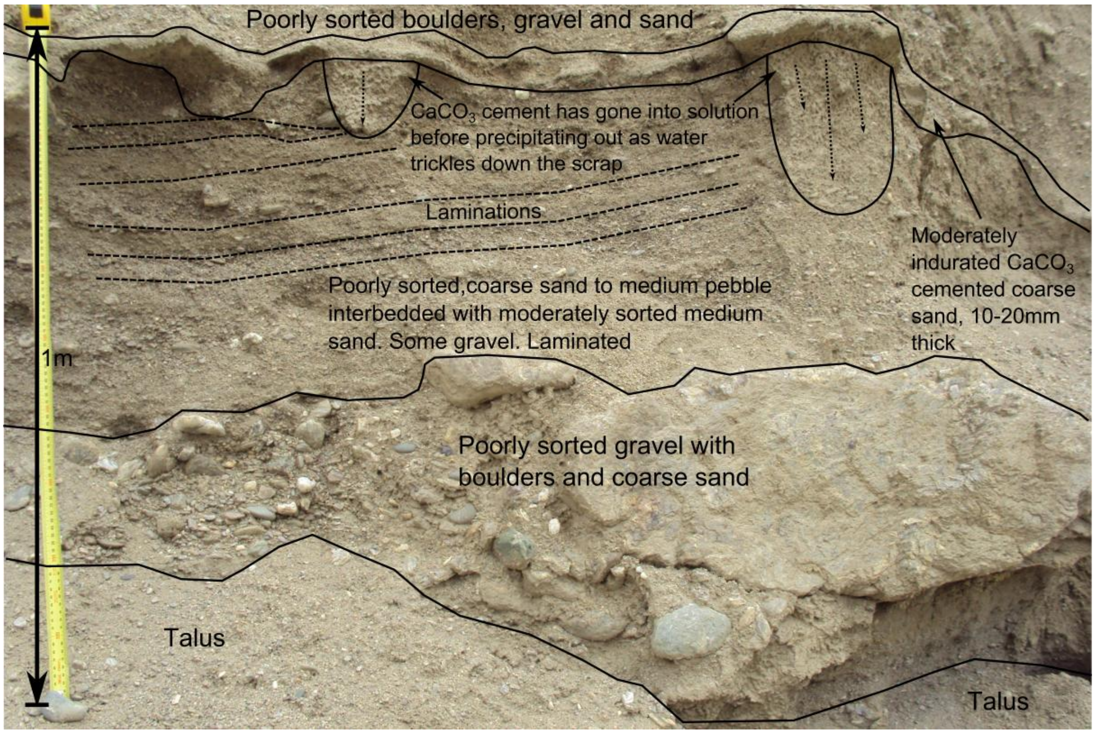


Figure 2.8 – Annotated photo graph of the Albert Town outwash gravels. Photo taken in scarp next to the Kawarau Arm. Note $CaCO_3$ band at top of photo. (Easting: 1296549 / Northing: 5002615)

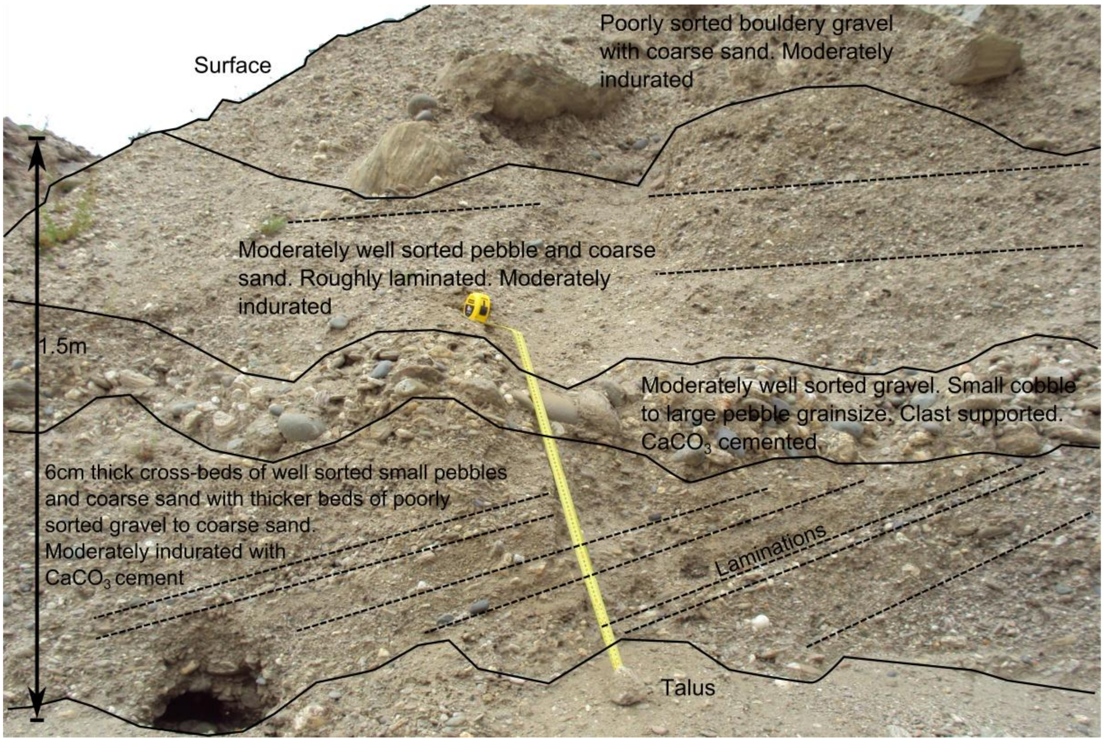


Figure 2.9 – Annotated photograph of the Albert Town outwash gravels. Photo taken in scarp next to the Kawarau arm. (Easting: 1296551 / Northing: 5002536)

It is unlikely that this calcium carbonate layer exists at deeper depths in the gravels below the water table and may just be a localised near surface phenomenon related to surface water percolation. It is unlikely to affect groundwater flow, but may affect surface water percolation down into the aquifer.

Cross bedding, buried channels and lenses of sand or fines will also control groundwater movement in the outwash gravels. Preferential groundwater flow will occur in buried channels and lenses of well sorted material. Cross bedding in the Albert Town outwash gravels can be seen in figure 2.9.

2.7 Chapter Summary

Outwash gravels derived from the Kawarau and the Clutha were identified from geological maps, field observations, bore log information and personal communications with Royden Thomson (Local Geologist) and Graham Stewart (Manager at McNeil Drilling). With this information a map of their surface extent was produced. The two outwash gravel formations that make up the CTA are the Luggate outwash gravels and the Albert Town outwash gravels. The Luggate outwash gravels are concentrated at the western side of the Cromwell Flat and include contemporaneous alluvial fan gravels along the base of the Pisa Range. The Albert Town Gravels make up the bulk of the gravel deposits on the Cromwell Flat, from about half way across the Flat to Lake Dunstan.

Due to anthropomorphic processes and surface cover from drifting sand, surface channel morphology isn't as obvious as it once might have been, but channels buried at depth exist in outcrops of cross bedded gravel in outcrops along the Kawarau Arm. Alluvial fans associated with the Luggate deposits and recent Holocene deposits are concentrated along the western side of the Cromwell Flat. Erosional features, like the Ripponvale Hill Tertiary sediment Mesa, are repeated at depth in the form of buried channels scoured into the Tertiary sediment surface.

The eroded surface of the buried Tertiary sediments provides the hydrological basement of the CTA and groundwater flow is likely to be concentrated in the buried channels of this surface. This surface also influences the availability of groundwater in certain areas of the Cromwell Flat as some Tertiary sediment topographic highs are above the groundwater table. Calcium Carbonate build up is unlikely to influence groundwater flow, but may affect surface water filtering down to the water table.

Chapter Three

Hydrogeology and Surface Hydrology

3.1 Introduction

The groundwater resources of the CTA are important as they help supplement the surface water resources of the Cromwell Flat. Groundwater provides water for domestic use, irrigation and frost fighting for many of the orchards and vineyards on the Cromwell Flat. An understanding of the hydrogeology of the CTA along with the surface hydrology of the Cromwell Flat is important to prevent over abstraction, or a reduction in groundwater quality occurring.

In this chapter, the surface hydrology of the Cromwell Flat and Pisa Range, and hydrogeology of the CTA are discussed. Surface hydrology is described in terms of catchment area, occurrence and flow rates. Information on surface hydrology was collected as part of this study to help better understand how Pisa Range surface flows interact with the CTA. The hydrogeology section of this chapter describes and evaluates the groundwater resources of the CTA in terms of its physical description, spatial and vertical distribution and groundwater flow direction determined by a groundwater level survey.

Interactions between Lake Dunstan and the CTA, along with long term effects of aggradation of the Kawarau Arm are discussed near the end of the chapter.

3.2 Surface Hydrology

Cromwell Flat and the Pisa Range have a very low rainfall rate of 439.6 mm/yr (climate data shown in figure 1.4) and a high evaporation rate of 1430 mm/yr (NIWA, 2010). This controls any surface flows in the area. Lake Dunstan is the largest and most dominant surface water body in the area. At Clyde dam, the Clutha River (Lake Dunstan) has an average annual low flow rate of 253 cubic metres per second (m^3/s) (O.R.C., 2010b).

The catchment of the Pisa Range and foothills that supplies runoff to the Cromwell Flat has a surface area of approximately 2078 hectares. Figure 3.1 shows the Pisa Range catchment and streams that transport water from the Pisa Range to the Cromwell Flat. The snowline during a visit to Cromwell for this study in August 2010 was at 609 masl. This snowline along with the snow – covered area of the catchment is shown in figure 3.1. The snow – covered catchment in August 2010 covered an area of 657 hectares. The catchment on the Pisa Range extends partially into the Kawarau gorge due to water races (figures 3.1 and 3.2) that intercept runoff that accumulates above it and divert water down into one of the 3 active streams that transports surface runoff to the Cromwell Flat.

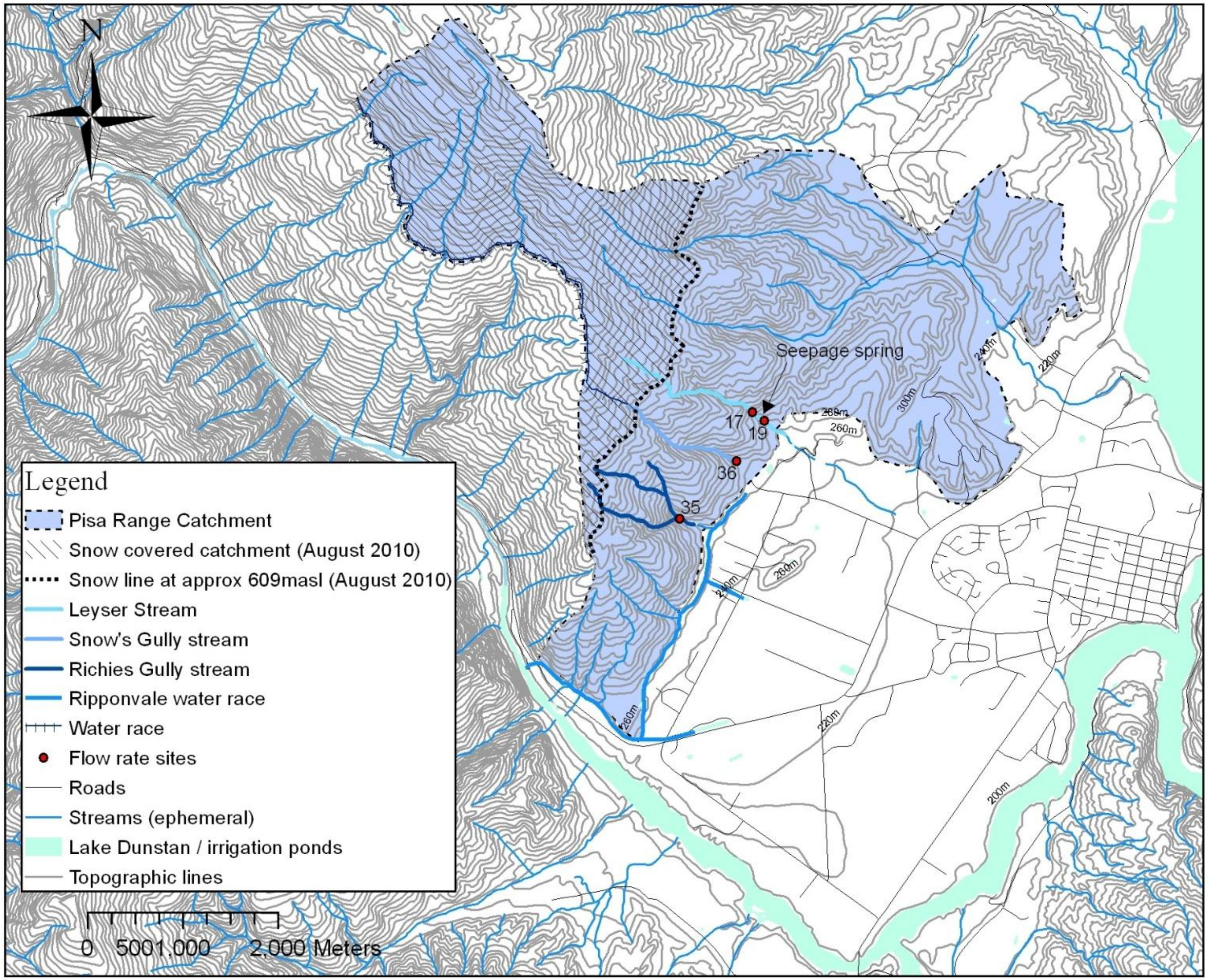
On Cromwell Flat itself, there are no natural surface flows but there are manmade canals and storage ponds that are part of the Ripponvale Irrigation Scheme. These channels transport water extracted from the Kawarau Arm across the Cromwell Flat and supply water to a number of orchards, vineyards and lifestyle blocks for irrigation, domestic use and frost fighting (Murphy & O.R.C., 2009). The Ripponvale water race is shown in figure 3.1.

The only natural surface flows in the area are small streams that flow off of the Pisa Range. There are 3 active streams that have year round flow, and a number of other drainages that had little to no flow in them during the course of this study, but erosion from water suggests that they are ephemeral.

The main streams off the Pisa Range that have measurable flow have been named as Richies Gully Stream, Snow's Gully Stream and the Leyser Stream for the purposes of this study. The locations and catchments for these three streams are shown in figure 3.1. Flow rates for these streams were measured by taking the time the stream took to fill 5 or 2 litre vessel. Sites for measuring flow rates were selected on accessibility and ability to be able to measure flow rates. Measurements were carried out at points in the streams where there was either a water fall, or where water was diverted into pipes for irrigation. Due to access issues, flow rates for these streams were only measured in autumn and winter (see appendix 3.2 for dates). This may affect the validity of the flow rate measurements as there are no summer or spring flow rate measurements that can be used for comparison.

The Leyser Stream flow rates were measured once at two sites during autumn (sites 017 and 019). The flow rates from each site on the Leyser Stream were then averaged to give a representative flow rate of the stream for this time of the year. Flow rates for Snow's Gully Stream (site 036) were measured once during winter. Richies Gully stream (site 035) had flow rates taken both in autumn and winter at the same site. For each visit to each site, a single measurement, consisting of a minimum of 5 flow rates were taken and then averaged to find the flow rate of the stream at that particular time of the year. Prior to the measurements made in autumn, there had been no rain for 8 days. The measurements made in winter were taken 2 days after a large snow storm that left snow

Figure 3.1 – Map showing the surface runoff catchment for the Cromwell Flat on the Pisa Range along with active streams and the sites where flow rate measurements were taken.



down to an elevation of 609 masl on the Pisa Range. Melting of the snow in the days prior to when the measurements were made would have increased the flow rate of the stream. Snow's Gully Stream would have been especially sensitive to snow melt as there is a water race above the Kawarau Gorge that diverts surface runoff and snow melt down into Snow's Gully Stream. Flow rates for the 3 streams are summarized in table 3.1 below. Appendix 3.2 shows calculations.

Site	Average flow rate (m^3/day)	Average flow rate for each stream (m^3/day)	Combined average flow rate for all streams (m^3/day)
Autumn			
Site 017	22		
Site 019	23	29	88
Site 035	43		
Winter			
Site 035	35	53	156
Site 036	70		

Table 3.1 – Summarized flow rate data for the Richies Gully Stream, Snow's Gully Stream and the Leyser Stream. Average flow rate for each stream is the combined average flow rate for a single stream. Combined average flow rate for all streams is the average flow rate for each stream multiplied by 3.

The average annual flow rate for all three of the Pisa Range streams combined during autumn is 88 cubic metres per day (m^3/day). In winter the value was calculated to be 156 m^3/day. The flow rate for site 035 was lower during winter by 8m^3/day than when it was measured during autumn. Site 036 has a much higher flow rate than any of the other streams. The higher flow rate for Snow's Gully Stream maybe due surface runoff on the slopes above the Kawarau Gorge being diverted into the stream via water races. Measurements for flow rate calculations at this site were carried out using a 2 litre vessel as opposed to the 5 litre vessel that was used other sites and may have created errors. Using a vessel with a smaller volume increases the amount of error when the flow rate is calculated later. A smaller vessel was used at site 036 as the larger vessel was not appropriate for taking measurements there. Unfortunately, no autumn flow rate measurement for site 036 could taken, so the winter flow rate of the stream could not be verified. The combined average autumn flow rate of 88 m^3/day was used for the calculations in the water budget (Chapter 5 and appendix 5.3) as the flow rate was calculated from more data points than the winter measurements.

Site 017 is located upstream of site 019 (figure 3.1) and from the flow rate measurements taken at each of these sites, site 019 was found to have a slightly higher flow rate than at site 017. This suggests that the stream is gaining water between site 017 and 019. A seepage point was observed above the northern bank of the Leyser stream, immediately uphill from site 019 (figure 3.3). Water from this seepage point maybe feeding the stream causing the increase in the flow rate. No measureable flow rate could be taken from the seepage point.

All of these streams have the majority of water diverted away for irrigation where each stream mets the Cromwell Flat (Figures 3.4). Water is collected in catch drums placed in the stream, with plastic pipes transporting water away. Old stream beds do not continue very far past these diversion points, indicating that the streams naturally would permeate into the Cromwell Flat.

Figure 3.2 - Photo of the water races that extend across the slopes above the Kawarau Gorge. These water races divert surface runoff from above them down into Snow's Gully stream. Photo taken looking north - west on the Pisa Range.

There are not a lot of springs around the Cromwell Flat or on the Pisa Range. The only spring of note was the seepage point observed near site 019 beside the Leyser stream as shown in figure 3.3. This seepage point covered an area of about 30m² and consisted of mud and small puddles of water.

This seepage point is likely to be a depression spring, but due to its location within the Pisa Fault zone, it could be fault spring (Fetter, 2001). Other springs that were observed were seepage zones near the heads of gullies in the Pisa Range catchment. These springs were no more than damp patches that varied in size from 1m² to 10m².

Figure 3.3 - Photo of the seepage point observed immediately upstream of site 019. Water seeps out in the muddy, ungrassed patch between the trees. Photo taken on the immediate northern side of the Leyser stream looking north.

Figure 3.4 - Photo of typical catch drum used to divert water away from streams for irrigation. This catch drum is site 019 near the end of the Leyser stream.

3.3 Cromwell Terrace Aquifer (CTA)

The CTA is an unconfined aquifer contained within a thin veneer of Quaternary gravels that vary in thickness from 10 – 20 m thick, although at the southern end of the Cromwell Flat the gravels in the buried paleochannels can be up to 50m thick. The Quaternary gravels are made up of permeable sandy and silty gravels with some boulders and localized lenses of silt, sand and clay. These gravels rest unconformably on less permeable folded Tertiary sediments. Depth to groundwater ranges across the Flat from -6m below the surface near the lake margin to -36m below the surface in the interior of the Flat.

3.3.1 Groundwater Cross-Sections

Groundwater cross-sections were created using bore log information from records kept by McNeil Drilling and the Otago Regional Council (O.R.C., 2010a; Graham Stewart, pers comm, 2010). Details for all of the bores used to create hydrogeological cross-sections are given in appendix 3.3. Physical descriptions of the geology for each bore are given in appendix 3.3.1. Three hydrogeological cross-sections were created from this data. These are shown in figures 3.6, 3.7 and 3.8. Locations of the cross-section lines are shown in figure 3.5. Figure 3.6 (cross-section A – B) was constructed approximately parallel to groundwater flow, where figure 3.7 (cross-section C – D) was constructed approximately perpendicular to groundwater flow. Figure 3.8 (cross-section C – E) was constructed roughly parallel to the southernmost paleochannel.

The cross sections show that the CTA is made up of massive sandy, silty gravels with localized lenses of silty sands. No regional stratification could be observed within the gravels from the cross sections. The localized nature of the sand and silt lenses is most likely due to the channelled nature of the gravels during deposition. No distinction between the older Luggate outwash gravels and the younger Albert Town outwash gravels could be observed from the bore logs as the geological descriptions were very brief. The contact between the two outwash gravels has been inferred from the terrace break at the surface of the Cromwell Flat and the contact between the Kawarau and Clutha derived gravels has been inferred from a map produced by Turnbull (1988). Contacts between the Tertiary sediments and the overlying gravels have been inferred from bore log information (O.R.C., 2010a) and seismic survey data (Modriniak & Marsden, 1938).

Groundwater levels used in the cross-sections were from the O.R.C. database (2010a). No dates were given for when the water levels for each bore taken, but it is assumed that all readings are pre 2010. Some bores did not have water level readings at all, so where possible, water level readings carried out during this study were used. Appendix 3.3 shows the groundwater levels used to create

Figure 3.5 – Map showing locations of hydrogeological cross-sections.

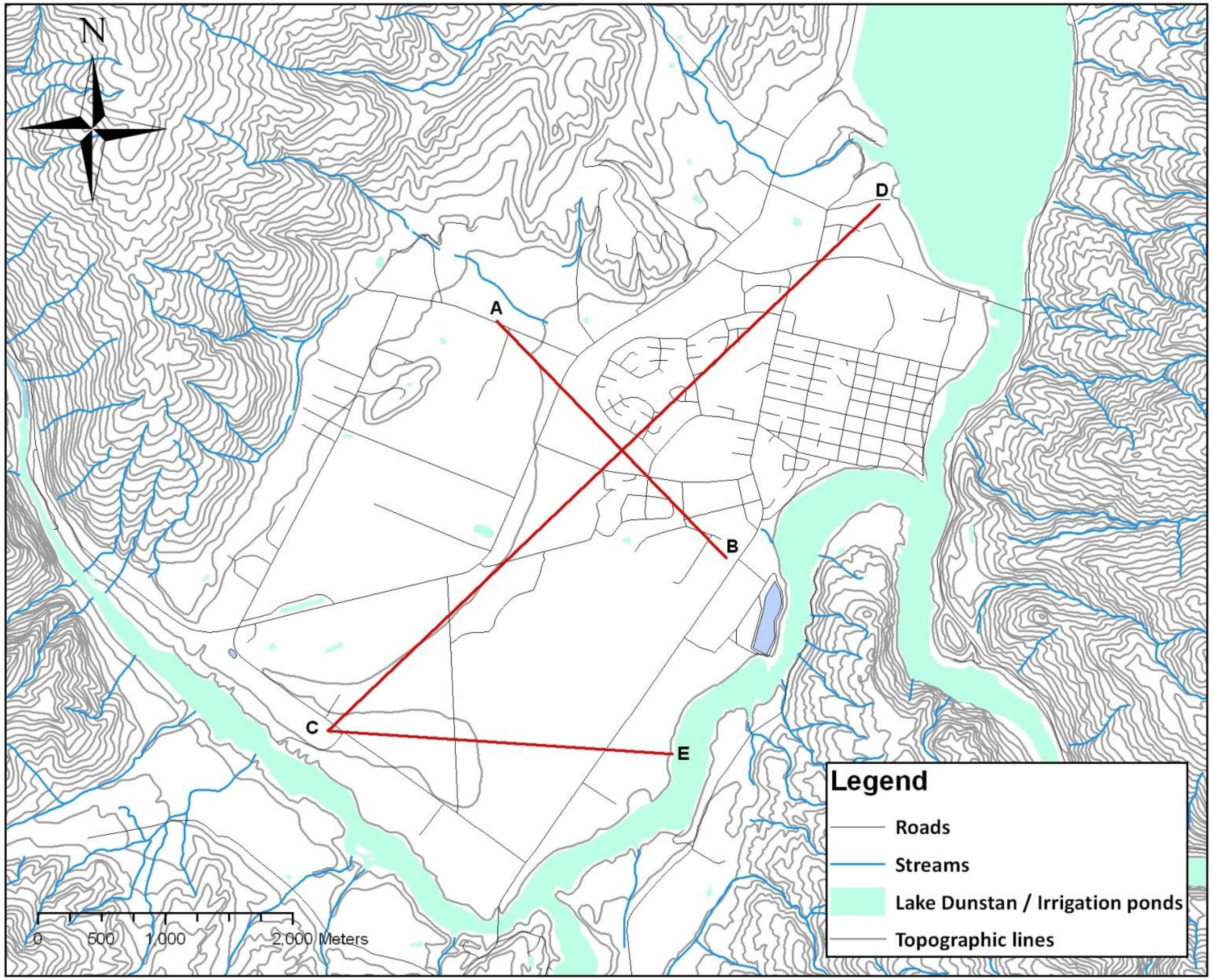


Figure 3.6 – Cross-section A – B approximately parallel to groundwater flow.

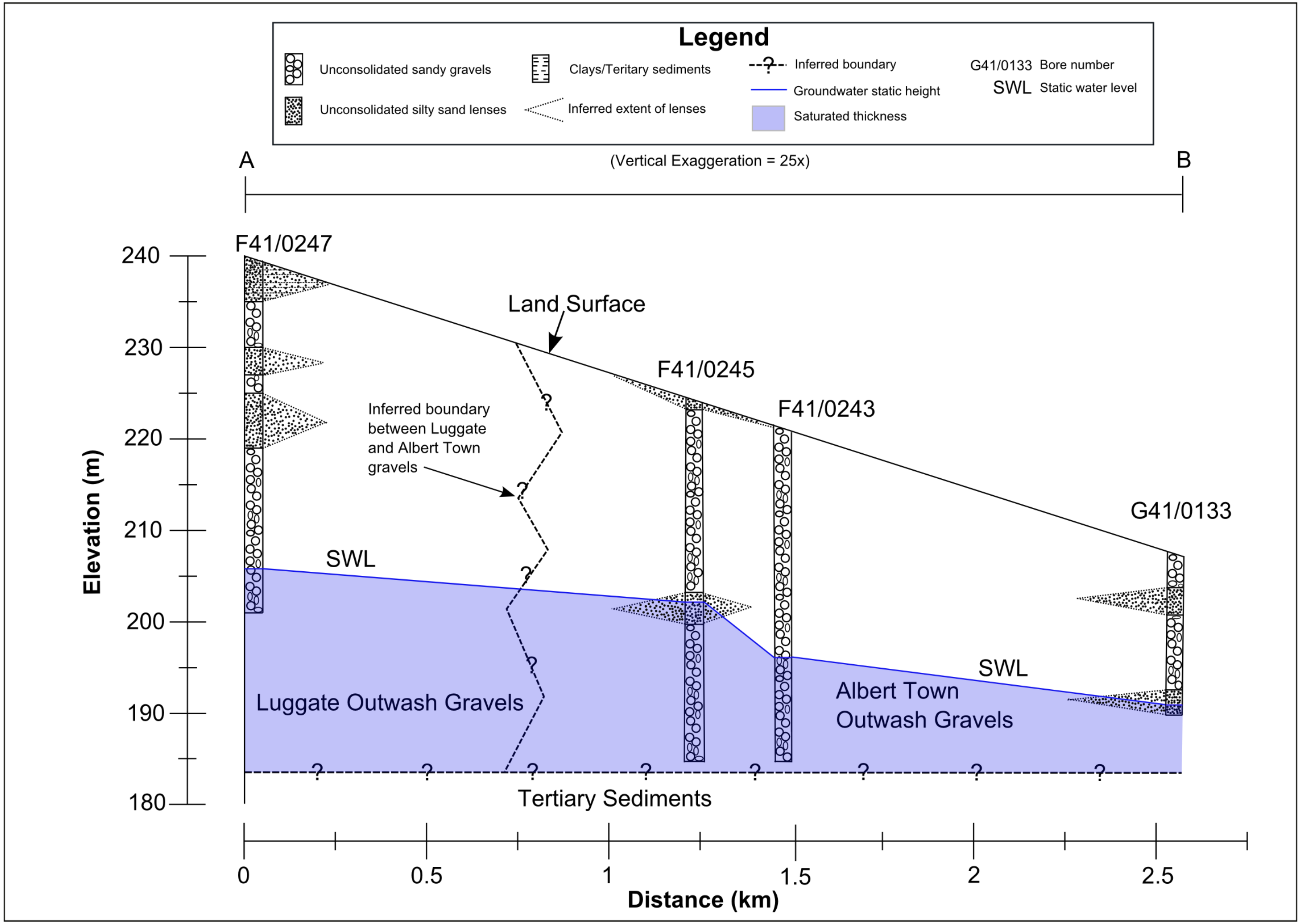


Figure 3.7 – Cross-section C – D approximately perpendicular to groundwater flow.

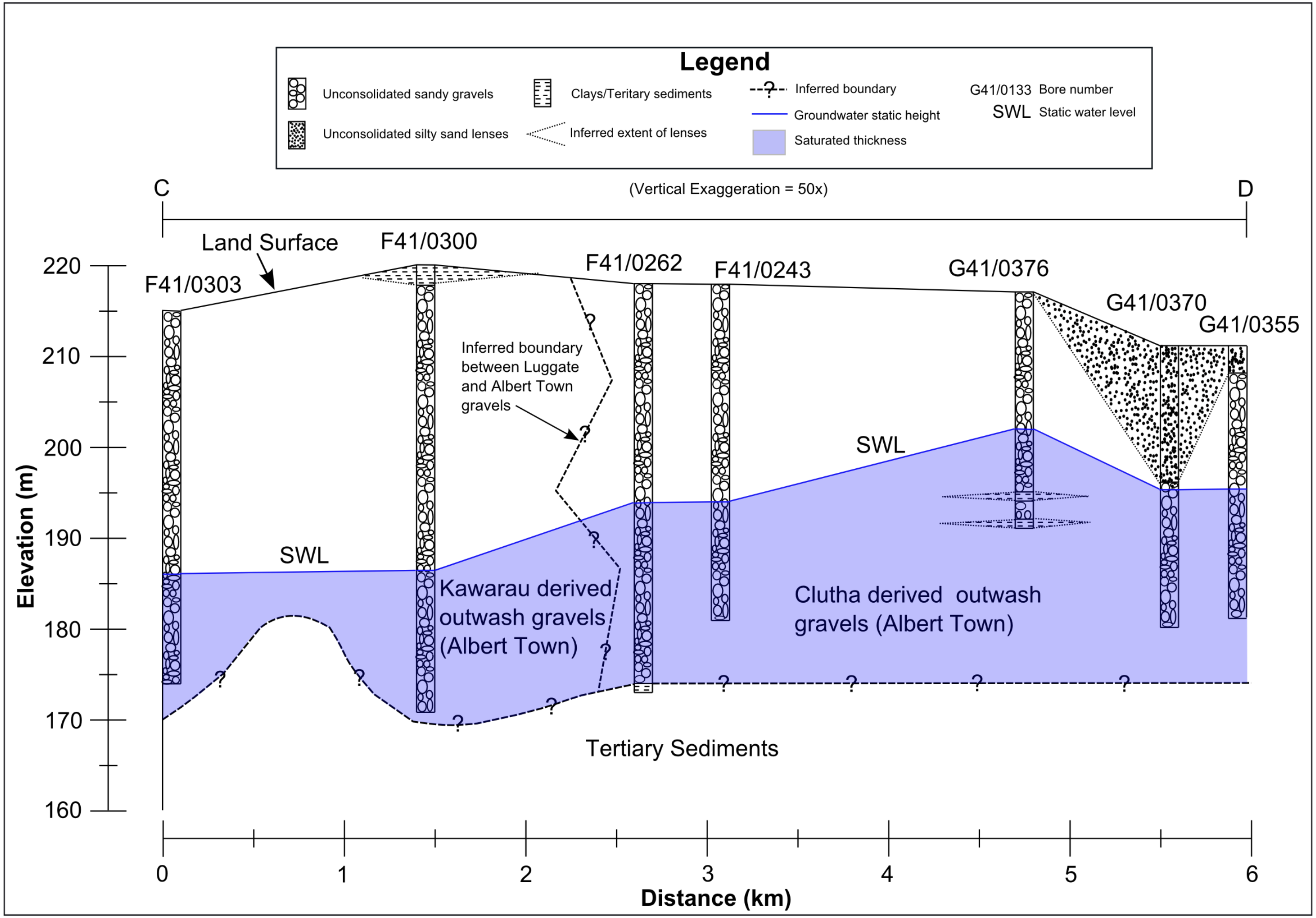
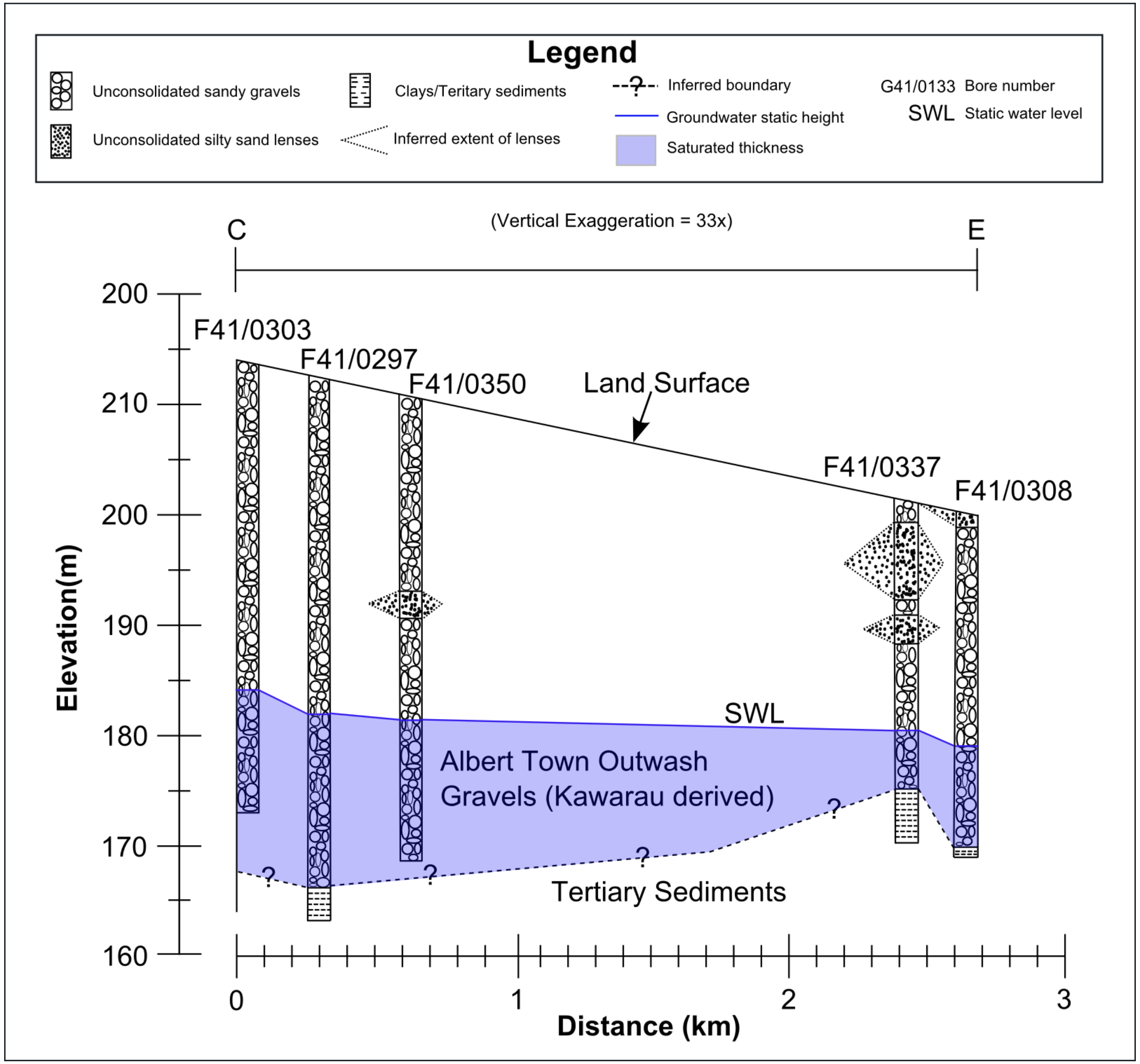


Figure 3.8 – Cross-section C – E approximately parallel to southernmost paleochannel.



the cross-sections. All cross-sections are vertically exaggerated.

All cross-sections show that the CTA is single unconfined aquifer in permeable gravels with a less permeable base made up by the Tertiary sediments. From the cross-sections, the saturated thickness of the CTA varies between 10 – 30 m, although this will depend on how deep the Tertiary sediments have been inferred. Figure 3.6 shows the groundwater level slopes gently toward to Lake Dunstan, although there is an increase in the slope between bores F41/0245 and F410243. Figure 3.7 shows the water table sloping gently to the south west and to the north east on either side of bore G41/0476. Figure 3.7 also displays the eroded surface of the Tertiary sediments that make up the paleochannels at the southern end of the Flat. The sides of these paleochannels make affect groundwater flow by changing flow direction or reducing flow to a bore during pumping, but the static water level is thought to be above most of the buried Tertiary sediment highs. Figure 3.8 shows the water table sloping gently off toward Lake Dunstan down the length of the southernmost paleochannel.

From figure 3.8, it appears that the Tertiary sediments shallow near the end of the cross section at E. This may be due to another buried Tertiary sediment high as shown in figure 2.7.

Figure 3.7 shows the Tertiary high between the two paleochannels to be below the water table. However, figure 2.7 showed that the buried Tertiary highs around the paleochannels may be above the water table between the two paleochannels. There may have been some errors from converting depths taken from the Modriniak and Marsden (1938) during the construction of the structure contour map, resulting in the elevated Tertiary highs. Thomson (2002) inferred in his diagrams that the Tertiary sediments projected above the water table, however modelling carried out by Rekker (2002) showed that the water table appeared to flow uninhibited across this area toward the Kawarau Arm. Based on the assumption that the Tertiary sediments are less permeable, any Tertiary high above the water table would affect groundwater flow but altering the direction of flow. Pump tests carried out by MWH NZ Ltd (2007) expected there to an influence from the sides of the paleochannel on the drawdown of the bore under investigation. No influences were observed suggesting, that there are no Tertiary sediment highs that are higher than the present water table of CTA. The elevation of these Tertiary highs can only be fully established by drilling and/or geophysics.

These cross-sections show that CTA is recharged near the western side of the Cromwell Flat and moves outward in an easterly direction through the aquifer toward Lake Dunstan.

3.4 Hydrological Properties of the CTA

The hydrological properties of an aquifer are a description of how easily water can move through the aquifer material and are typically described in terms of hydraulic conductivity, transmissivity and storativity. Hydraulic conductivity (K) or the coefficient of permeability is found from Darcy's Law which shows that the rate at which water can flow through a particular medium is proportional to the change in head (Fetter, 2001). Hydraulic conductivity normally has units expressed in metres per day (m/day) and can be found from the equation:

$$Q = -K \times A \times (dh/dl)$$

where Q = discharge (m), A = cross-sectional area *dh* = change in head (m), *dl* = change in length and *dh*/*dl* is the hydraulic gradient.

Transmissivity (T) is the rate at which water can be transmitted through a horizontal unit width of the aquifer under a unit hydraulic gradient (Fetter, 2001). Units are typically expressed as metres squared per day (m^2/day). Transmissivity is found using the equation:

$$T = b.K$$

where *b* = saturated thickness of the aquifer in metres (m)

Storativity (S) or the storage coefficient is the volume of water that an aquifer will absorb or expel per change in unit head, per unit surface area (Fetter, 2001). Storativity is dimensionless and can be found using the following equation:

$$S = (dV/dh) / A$$

where *dV* = Volume of water absorbed or expelled from aquifer.

The hydrological properties of an aquifer are normally found from performing pump tests on a particular bore. Water is extracted from the bore at a known rate for a particular amount of time and the change in the water level in the bore is measured. The length of time over which water is extracted can range from minutes to days, depending on geologic and hydrogeologic properties of the aquifer. Observation bores are monitored during a pump test to try and determine the influence of pumping from a particular bore on other neighbouring bores.

Typically, pump tests are carried out as either a constant discharge test where water is extracted from the bore at the same rate for the entire test, or as a stepped discharge test where the rate at which water is extracted is increased and then reduced over time (Fetter, 2001). When pumping has stopped, recovery of the groundwater level in the bore is measured over time to determine how long the water table takes to recover back to its original height (Fetter, 2001).

Unfortunately, adequate pump test data for the CTA is limited to just one pump test, resulting in little knowledge of the hydrological properties of the CTA. This pump test was carried out during the installation of bore F41/0350 (Easting: 1297602 / Northing: 5002362) near the southwestern end of the Cromwell Flat. The pump test was only carried out on this bore and the data collected from the test was used to determine the hydrological properties of the aquifer around this bore. The hydrological properties of the aquifer around this bore were required to help satisfy the requirements of a resource consent to extract water for irrigation at a rate of 30 litres per second (L/s) (MWH NZ Ltd, 2007). Processing of the pump test data and modelling were carried out by MWH NZ Ltd. (2007) in conjunction with the O.R.C. The findings from this investigation are shown below in table 3.2.

Hydraulic Conductivity (m/day)	45 – 66
Transmissivity (m^2/day)	750 – 800
Storativity (dimensionless)	0.07 – 0.2

Table 3.2 – Hydrological properties of the CTA from MWH NZ Ltd. (2007).

Glacial outwash gravels are known to allow good groundwater flow through them and typically have hydraulic conductivities in the range from 1 – 86 m/day (Fetter, 2001). The hydrological properties of the CTA are reasonably representative of other unconfined glacial outwash gravel aquifers found in the Clutha River Valley. The Earnscleugh Aquifer, in the Alexandra Basin about 25 km south west of Cromwell, is an unconfined aquifer made up of Lindis outwash gravels on top of the same less permeable Tertiary sediments and Otago Schist as the CTA. The Earnscleugh Aquifer has a hydraulic conductivity of 100 m/day and a transmissivity of 700 m^2/day (Bekesi, 2005). Transmissivities of the Clutha River Valley aquifers are considerably lower than the transmissivities of the glacial outwash gravels found on the Canterbury Plains. Transmissivities here are in the range of 1000 m^2/day to 10,000 m^2/day (Vincent, 2005).

Bore F41/0350 is located in the Southern most paleochannel in Kawarau derived Albert Town outwash gravels. Hydrological properties of the aquifer may vary between the Clutha derived Luggate and Albert Town gravels and between the Kawarau derived Luggate and Albert Town gravels. From the groundwater cross-sections, it appears that there is not much variability in the gravels, but this may be due to limited information for each bore hole. More pump tests would need to be carried out across the Cromwell Flat in both the Luggate and Albert Town gravels and also the

Kawarau and Clutha derived material to determine if the hydrological properties of the CTA vary across the Flat.

3.5 Groundwater Flow

Groundwater level surveys were carried out for the CTA four times throughout this study with surveys coinciding roughly with each season. Measurements were taken approximately every three months, with the first measurements taken in May 2010 during autumn. Winter measurements were taken during August 2010, spring measurements during November 2010, and summer

				DTW (masl)			
Bore	**Elevation of bore collar (masl)**	**Easting**	**Northing**	**Autumn**	**Winter**	**Spring**	**Summer**
F41/0155	231	1296645	5002627	202.30	202.30	202.30	202.30
F41/0168	232	1299923	5003384	-	213.10	213.14	213.04
F41/0171	240	1297934	5003474	-	205.80	205.87	205.60
F41/0247	239	1298357	5005711	204.03	204.07	204.26	204.00
F41/0268	230	1296722	5002583	201.40	202.73	202.90	203.85
F41/0297	227	1297270	5002391	197.49	198.31	198.47	200.64
F41/0300	240	1297971	5003508	206.80	206.73	206.63	206.77
F41/0316	225	1299651	5002977	-	205.79	205.87	205.90
F41/0318	239	1296118	5003310	-	203.00	203.80	203.60
F41/0337	212	1299388	5002100	190.90	190.61	190.61	190.40
G41/0122	227	1302071	5005654	-	-	211.20	212.26
G41/0256	222	1300159	5006346	203.60	203.31	203.31	203.42
G41/0351	210	1301558	5006306	199.15	198.60	198.95	198.99
G41/0365	214	1301333	5006424	199.10	198.86	198.82	198.90
G41/0370	224	1300973	5006300	208.54	208.16	208.25	208.19
G41/0371	213	1301175	5006557	197.77	197.60	197.59	197.65
G41/0376	216	1300248	5005434	-	203.60	203.62	203.65

Table 3.3 – Water levels in selected bores across the Cromwell Flat taken during the course of this study (March 2010 – March 2011).

measurements taken during February 2011. A total of 17 bores were monitored during the course of this study, with two of them (F41/0297 and F41/0300) being remotely monitored by the O.R.C. These two bores have their water levels measured only three times a year during March, June and September. Measurements from March 2010 were considered be autumn measurements, June 2010 measurements winter measurements, September 2010 spring measurements and March 2011 to be summer measurements. Measurements made during this study were carried out using a portable analog water meter. A sensor on the end of cable is lowered down the bore, and when the sensor reaches water, a light on meter at the surface lights up. The depth to water can be measured off the cable which has meter (m) and centimetre (cm) increments. Measurements were taken when the bore was not being pumped, although it was not known whether or not pumping had been carried out just prior to measuring. Locations of the bores which were monitored during this study are shown in figure 3.9.

The results of the groundwater level measurements carried out during this study are displayed in table 3.3.

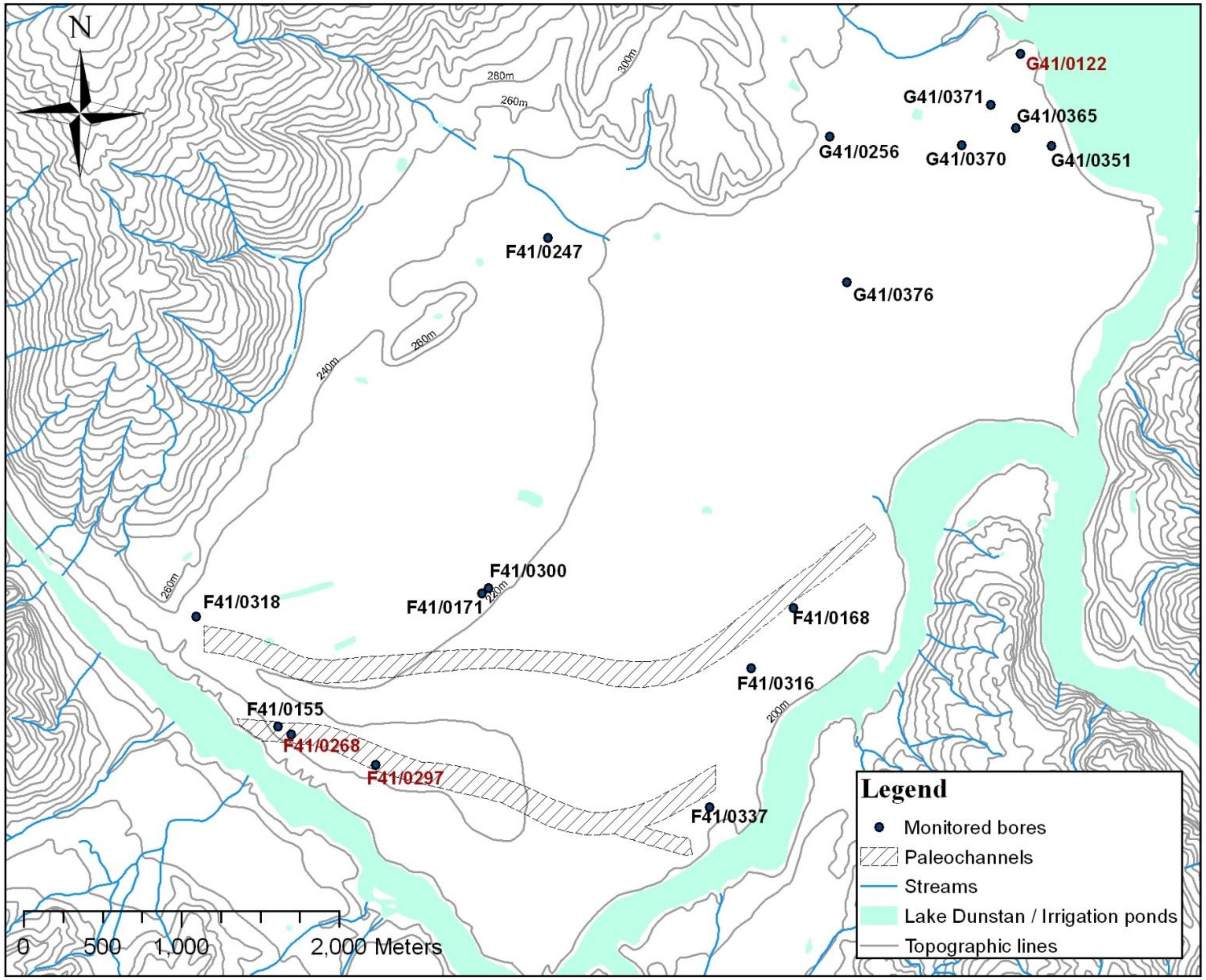
Depth to groundwater varies from 11 m to 35 m below the surface of the Cromwell Flat. Depth to groundwater increases away from the lake margin, with deepest depths being closer to the base of the Pisa Range. Information from the O.R.C. database (2010a) suggest that water levels are generally just slightly lower during winter compared to other seasons, although levels in most bores were relatively stable throughout the study with most fluctuations being in the range of 0.1 – 0.5 m. Bores G41/0122, F41/0297 and F41/0268 had notable differences in the groundwater level with changes of 1m, 2.13m and 2.45m respectively. These bores are highlighted in red in figure 3.9. Due to the relative stability of groundwater level measurements in the other bores, the large differences observed in these bores may be from pumping just prior to the measurements being taken. More measurements from these bores are required to determine if the large fluctuations are anomalous.

The operating levels of Lake Dunstan range between 193.5 and 194.5 masl but on average from 1993 to 2002, the lake surface elevation has been relatively constant at 194.5 masl (Madin, 2002). During this study, lake surface elevation measurements were taken during each visit to the Cromwell Flat to monitor groundwater levels. These measurements found the average surface elevation of Lake Dunstan to be 194 masl.

Groundwater level measurements taken during this study were then used to construct static groundwater level contour maps for each season. Each contour line represents points of equal height for the static CTA groundwater table above mean sea level.

Arrows were drawn at right angles to indicate groundwater flow direction. Lake Dunstan is shown around the edge of the Cromwell Flat at 194 masl. Static groundwater level contour maps for each season can be viewed in figures 3.10, 3.11, 3.12 and 3.13. Groundwater flow lines are shown in figure 3.13.

Figure 3.9 – Map showing location of bores that were monitored during the course of this study. Bore numbers highlighted in red had water level fluctuations greater than 0.5 m during monitoring.



The results of the measurements from bore F41/0337 appear to be anomalous. All groundwater measurements for this bore show that the water table is below lake level. This means that lake water should be flowing into the aquifer around this bore, and that the water extracted from this bore would be a mixture of lake water and groundwater.

Due to the consistency of the levels for this bore, it could be suggested that the elevation of the bore collar may be incorrect. This is made more likely by the fact that the neighbouring bore (F41/0316) is at a higher elevation than bore F41/0337, and if the elevation of bore F41/0316 is used for bore F41/0337, the groundwater levels would be above the level of Lake Dunstan. Furthermore, the stable isotopic signature (discussed in chapter 4) for this bore suggests that the water extracted from the bore is groundwater and not lake water. From this it has been assumed that the elevation of the collar for bore F41/0337 is incorrect, resulting in the depth to groundwater measurements for this bore being incorrect also.

The groundwater level contour maps show that there is little change in the water table between seasons with fluctuations ranging from 0.1 – 0.5m for the entire year. This may be due to the poor spread of data over time (water level measurements only recorded for one year). The groundwater level contour maps also show that groundwater flows outward from the Pisa Range toward Lake Dunstan and the Kawarau arm. The contours tend to be closer together where there are more bores and are closer to the lake margin. In contrast, there are fewer bores in the middle of the Cromwell Flat and the contours are more widely spaced apart.

These contour maps indicate that recharge is from the Pisa Range and Burns Cottage Rd. Valley, with groundwater flowing outward from these two points toward Lake Dunstan in southeasterly and southwesterly directions.

Hydraulic gradients varied from 5 m/km in the middle of the CTA and steepened significantly near the lake margin up to 22 m/km.

3.6 Groundwater Level Fluctuations

No obvious seasonal variations were observed from the monitoring carried out during this study, but monitoring of bore F41/0350 over a period of 7 years shows that there are strong seasonal variations in the CTA (Thomson, 2004). Measurements were taken to monitor the effect of Lake Dunstan on the CTA while the lake was being filled and any impacts it had after filling. Groundwater level measurements were taken at least once a month and sometimes up to 4 times in one month, for a total of 7 years. Figure 3.14 shows a plot of these measurements. The filling of Lake Dunstan

Figure 3.10 – Autumn static groundwater level contour map for the CTA.

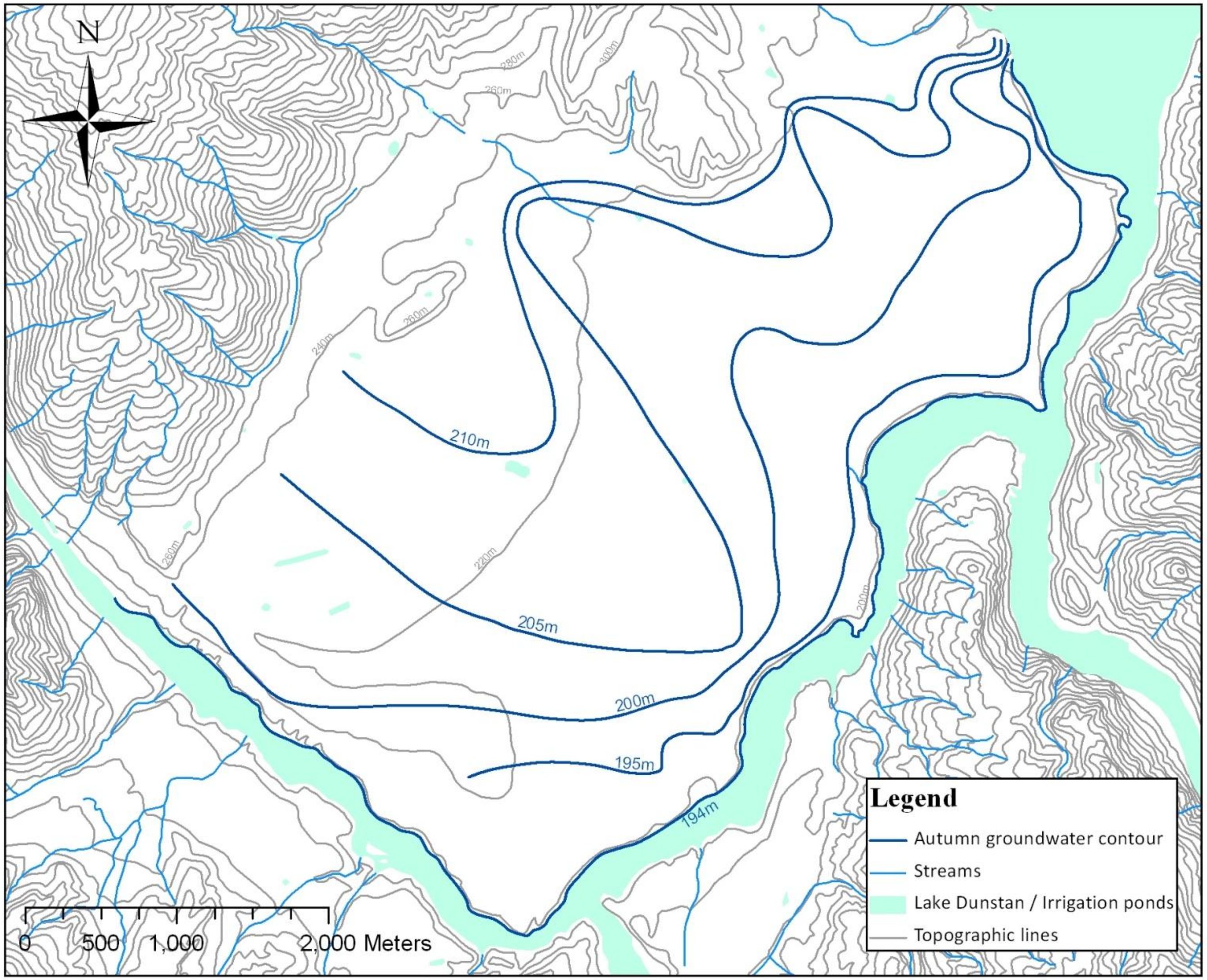


Figure 3.11 – Winter static groundwater level for the CTA.

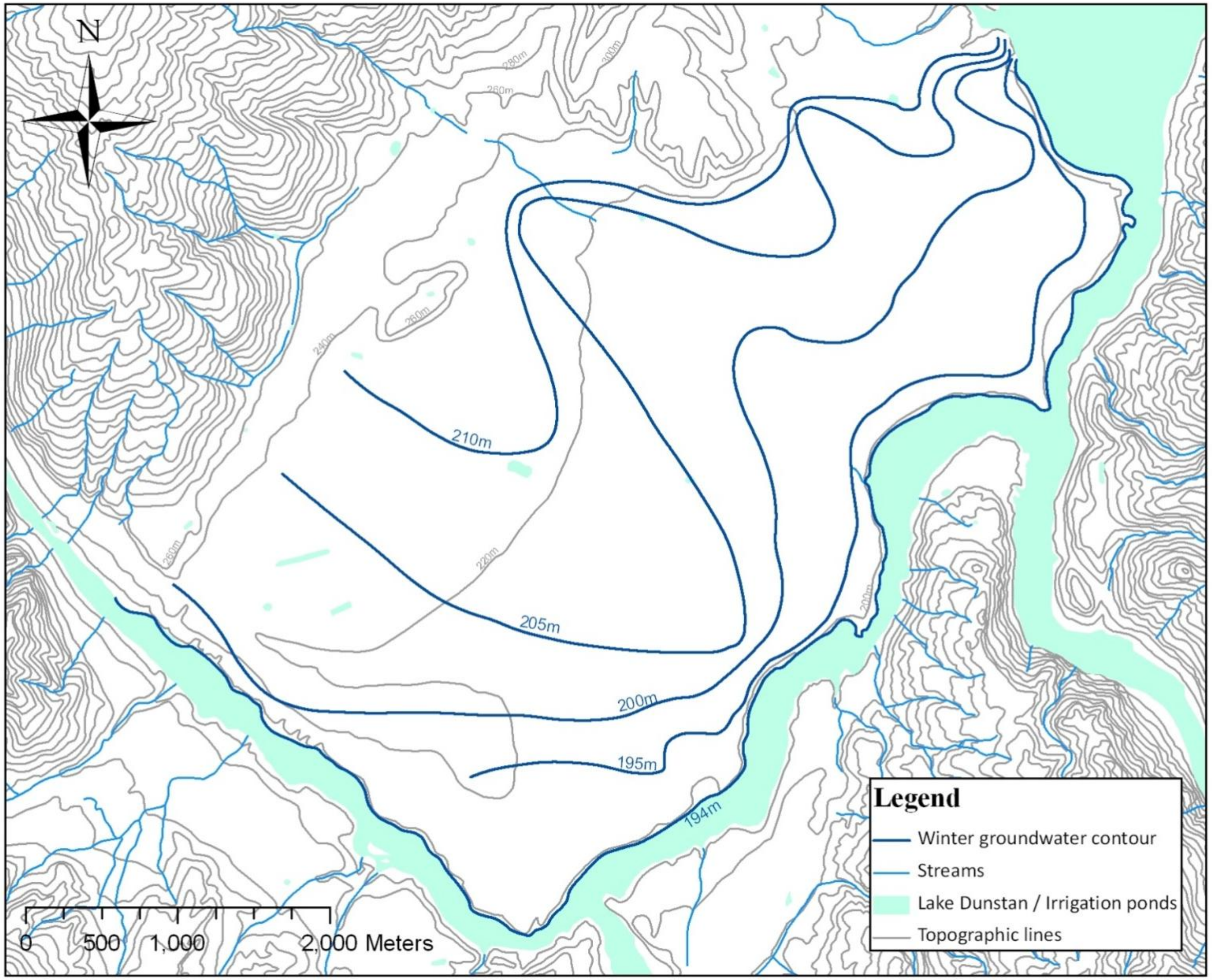


Figure 3.12 – Spring static groundwater level contour map for the CTA.

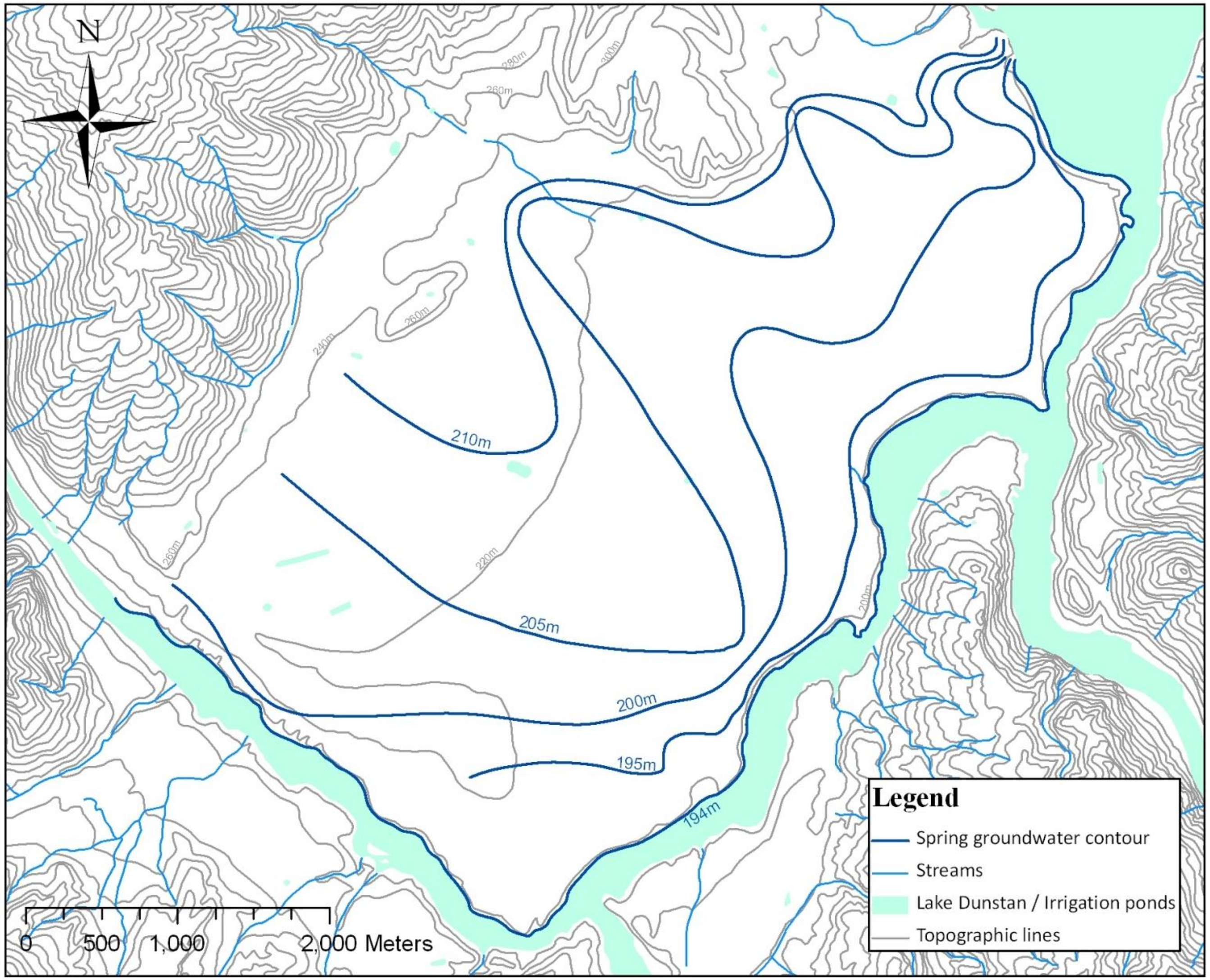


Figure 3.13 – Summer static groundwater level contour map and groundwater flow direction lines for the CTA.

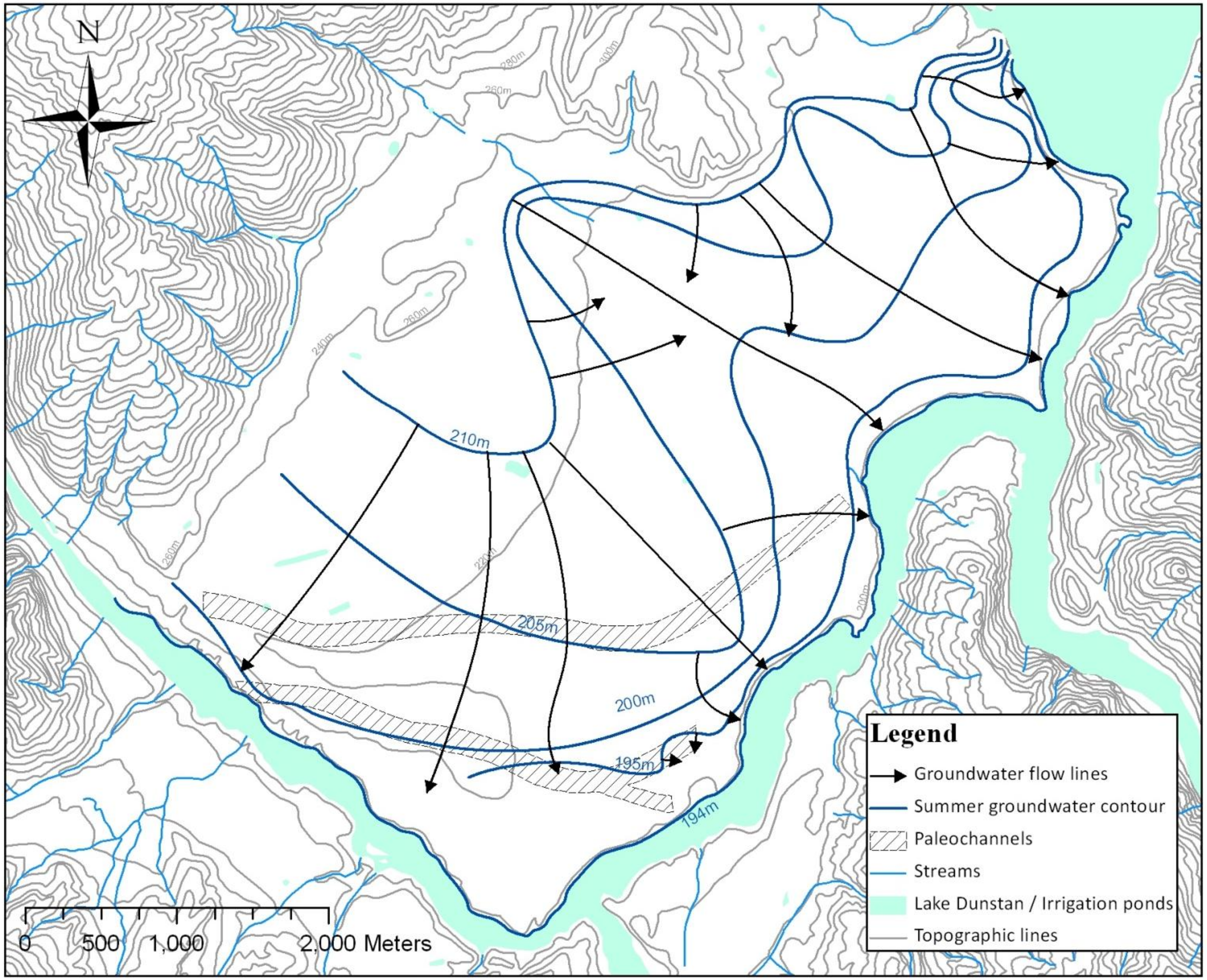
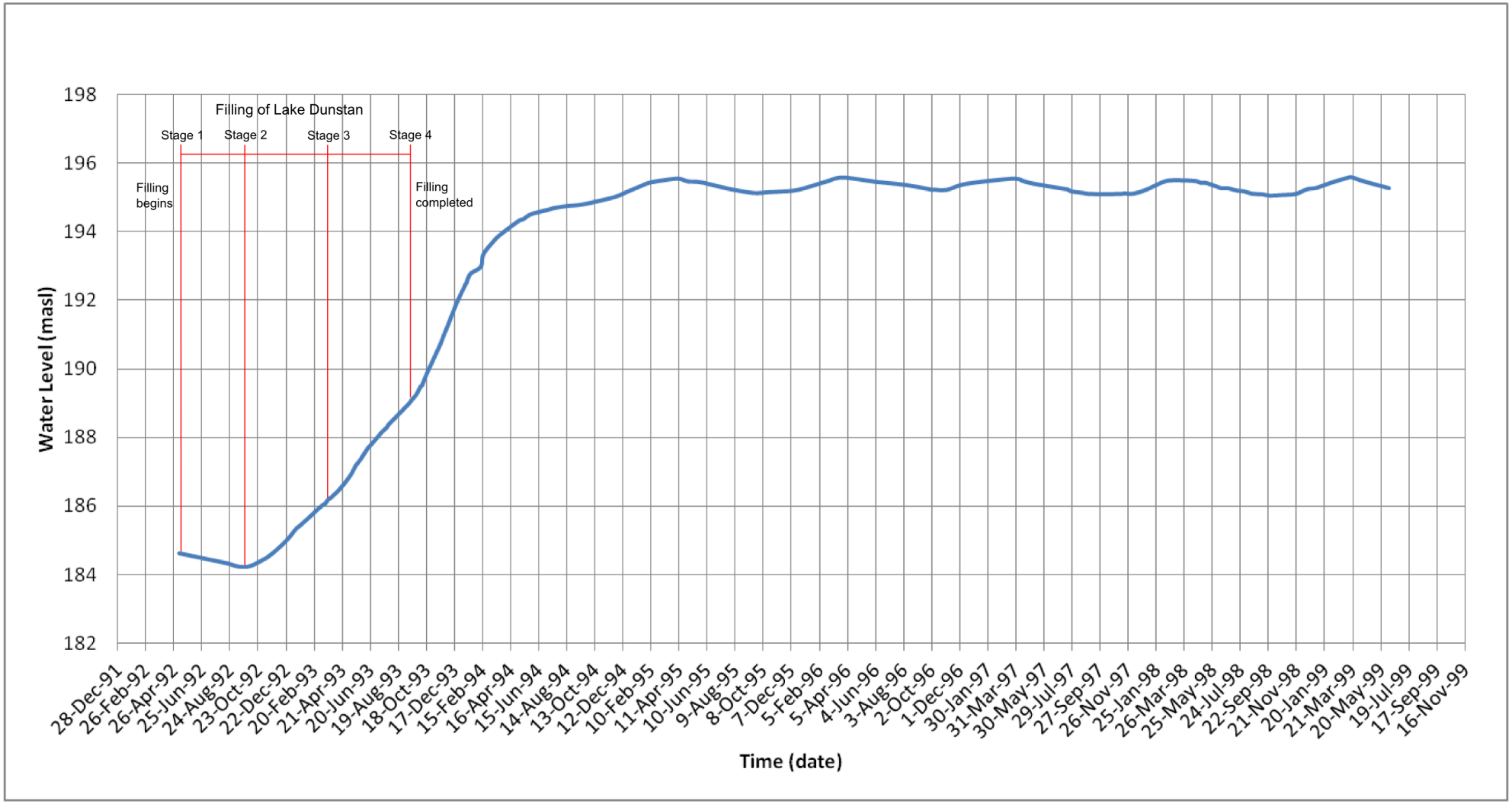


Figure 3.14 – Plot of groundwater levels for the CTA from the Muller bore F41/0350. Measurements were taken over a 7 year period. The filling of Lake Dunstan and seasonal variations in the CTA groundwater table are shown. From Contact Energy data base (Thomson, 2004).



raised the original height of the groundwater table in the bore by approximately 11 m.

Fluctuations in the water table are about 0.4 – 0.5 m over the course of one year with the maximum groundwater table level being 195.6 masl and the minimum level being 195.1 masl. The maximum levels of the water table occur in late March / early April and the minimum levels in late September / early October. The maximum levels coincide with the end of summer / start of autumn and the minimums during the end of winter / start of spring. Since the lowest amount of rainfall occurs in winter and the highest amounts of rainfall generally occurring during summer, it would appear that recharge to the CTA is controlled by seasonal rainfall. However, irrigation is most intensive during the summer months as well, and may artificially recharge the aquifer during this period. Seepage from the Ripponvale Irrigation Scheme canals and storage ponds may also recharge water to the CTA during the summer months. The fluctuations in groundwater levels during summer maybe attributed to both of these artificial recharge sources, as well as higher rainfall during this period. More information is required to help pin point the source of these seasonal fluctuations.

The groundwater level heights after the filling of Lake Dunstan are very consistent. Between each maximum and minimum groundwater level, the water table drops and rises relatively consistently, creating the roughly sinusoidal plot shown in figure 3.14. This is due to Lake Dunstan being held at a constant level of 194.5 m for the vast majority the time since it was filled (Madin, 2002; MWH NZ Ltd, 2007).

Groundwater levels in the CTA are controlled in the long term by Lake Dunstan, but since Lake Dunstan is maintained at a very constant level, there are unlikely to be any long term changes in the levels of the CTA. Seasonal variations are the only variation in levels of the CTA, although these are very small. Some larger variations were observed in the groundwater level measurements (>0.5 m) carried out during this study, but these have been attributed to the bores being pumped just prior to measuring. If there is a large increase in the amount of groundwater extracted, then may be some changes in groundwater level, especially during the summer months as the demand of water for irrigation increases.

3.7 Aggradation of the Kawarau Arm

With the filling of Lake Dunstan, it was predicted that the newly formed Kawarau Arm would eventually be in filled with sediment deposited by the Kawarau River as it exits the narrow Kawarau Gorge out into the Kawarau Arm (Madin, 2002). Aggradation or ‘siltation’ of the Kawarau Arm is the result of the abrupt change from the narrow, fast flowing, high energy fluvial environment in the

Kawarau Gorge exiting into a wider, slow flowing, low energy lacustrine environment (Madin, 2002). The change in environment allows fine sediment such as silt and fine sand that is carried in suspension to drop out of the water column and form a lake delta. During high flow events, larger sediment such as gravel can be transported from the Kawarau Gorge via bedload processes and deposited on the delta (Madin, 2002). Since the filling of Lake Dunstan, siltation of the Kawarau Arm has occurred much faster than predicted. Based off observations from aggradation of Lake Roxborugh, it was predicted that it would take 30 – 40 years for the delta front to reach Cromwell Township (Madin, 2002). During the mid 1990's, immediately after the filling of Lake Dunstan, the region experienced a number of major flood events in succession which greatly speeded up the siltation process and reduced the length of time it would take for the front to reach Cromwell Township (Madin, 2002). In a report prepared by Madin (2002) for Contact Energy, it was thought that the successive major flood events during the 1990's were anomalous and that siltation would still take the original prediction of 30 – 40 years to completely fill the Kawarau Arm with sediment. Madin (2002) discussed the resulting environment of the fully aggraded Kawarau Arm, suggesting

Figure 3.15 – Kawarau Arm as of the 17 of November 2010. Note the gravel bars forming in the centre of the river and along the left hand bank. Photo looking southwest. (Easting: 1296407 / Northing: 5002607)

that it would be a meandering – braided river system with 1 or 2 major channels and flood plains on either side. River height is likely to be raised above present lake level, increasing the maximum flood height.

Many bores on the Cromwell Flat are near the edge of lake margin of the Kawarau Arm and it is thought that most of these bores abstract a mixture of groundwater and lake water that has infiltrated into the CTA. Before the filling of Lake Dunstan, anecdotes recall water in some of the mine shafts sunk into the paleochannels, flowing in a similar direction to the Kawarau River (Thomson, 2002). This was thought to be the result of water flowing through the bank of the

Kawarau River where it exited the Kawarau Gorge. Siltation of the Kawarau and the resulting change in environment may reduce the amount of lake water infiltration into the CTA, as silt will fill pore spaces in the gravels along the margins of lake. Siltation is only thought to fill pore spaces a few cm into the lake margin gravels (Madin, 2002). Even so, this may be enough to reduce any flow of water from Lake Dunstan into the CTA and the amount of water that can easily extracted from bores on the lake margin.

3.8 Chapter Summary

Surface flows in the Cromwell area are very limited and are restricted to 3 small streams from off of the Pisa Range. The majority of this water is taken for irrigation.

Cross-sections of the hydrogeology of the CTA were produced from bore log descriptions and water levels showing that the CTA is a single unconfined aquifer, with a saturated thickness that ranges between about 10 m and 30 m.

Hydraulic conductivity, transmissivity and storativity data show that the aquifer allows water to flow with relative ease through the system. The hydraulic conductivity of the CTA was found to be 45 - 66 m/day, the transmissivity in the range of 750 – 800 m^2/day and the storativity in the range of 0.07 – 02.

Groundwater level contour maps show that groundwater flows outward from the Pisa Range and Burns Cottage Rd. Valley toward Lake Dunstan in south easterly and south westerly directions. This indicates recharge from the Pisa Range.

Groundwater fluctuations are seasonal and range between late summer maximums of 195.6 masl and late winter minimums of 195.1 masl. Rainfall maximums in summer suggest that the higher groundwater table levels observed in summer are the result of recharge from rainfall. However, summer is the main irrigation season, and the fluctuations may also be due to artificial recharge from irrigation and seepage from the Ripponvale Irrigation Scheme canals and storage ponds.

Aggradation in the Kawarau Arm may pose a problem to bores near the lake margin due to silt filling up void spaces of the gravels that border the lake. This may reduce lake water infiltrating into the aquifer.

Chapter Four

Groundwater Chemistry and Stable Isotopic Analysis

4.1 Introduction

Water samples were collected for chemical analysis from selected wells, springs and surface waters, to identify chemical characteristics of the groundwater resources and hydrogeologic orders.

Groundwater chemistry was first investigated in Cromwell as part of an investigation into the Upper Clutha Valley during the development of the Clyde Dam Hydroelectric Project (Close & McCallion, 1988). More recently, the Otago Regional Council (O.R.C.) has been monitoring groundwater and surface waters of the Cromwell Flat for a number of years prior to this study as part of its annual state of the environment reports. The majority of bores across the Cromwell Flat have been monitored since 1998, depending on when they were installed. Monitoring and sampling of Lake Dunstan has been carried out since the early 1990's when Lake Dunstan was filled. Chemical sampling and monitoring is an ongoing process and continues to the present.

Parameters that have been analysed from chemical sampling and monitoring by the O.R.C. include: alkalinity, coliforms, conductivity, pH, temperature, total dissolved solids, total hardness, and major cations and anions (e.g. Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, SO_4^{-}, HCO_3^{-}, Cl^{-}, CO_3^{-}, NO^{3-}, Fe^{3+}, Fe^{2+}, Mn^{2+}). Unfortunately, over the years, the number of parameters analysed by the O.R.C. has decreased for each sample site, and recent chemical sampling only focused on analysis of coliforms, conductivity, nitrate, pH and temperature. Since groundwater classification studies require major ion chemistry data, most of the recent data collected by the O.R.C. cannot be used for hydrochemical analysis. Due to a lack of funding, this study was unable to independently carry out a separate chemical sampling programme of selected wells, springs and surface waters for all major cations and anions for the same hydrologic year. The data collected by the O.R.C. used in this study was collected over a number of different years, not the same hydrologic year. This has restricted this study and may affect the validity of the results as seasonal changes in water chemistry in the CTA can't be observed.

However, samples collected as a part of this study were analyzed for stable isotopic compositions. These data were used to better define the sources of recharge to the CTA and understand the hydrogeologic processes involved with groundwater movement in the CTA. The stable isotopes used in this study were ^{18}O and ^{2}H. Samples were collected from all water sources in the Cromwell Flat area and the stable isotopic signature for each water source compared to determine sources of recharge to the CTA.

4.2 Previous Water Chemistry Investigations

During the mid 1980's, Close and McCallion (1988) carried out a groundwater chemistry survey of the Cromwell – Tarras basin during the development of the Clyde Hydroelectric Project, to try and assess the effects Lake Dunstan would have on groundwater in the affected area. Sample sites were spread throughout the basin, which included three bores on the Cromwell Flat. These three sample sites are shown in figure 4.1. Samples were analysed for major ion chemistry (Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-}) and some minor ions (Fe^{3+}, Mn^{2+}, PO_4^{2-}). Samples were collected over a 12 month period from November 1982 to November 1983. A summary of the results from this study are shown in table 4.1.

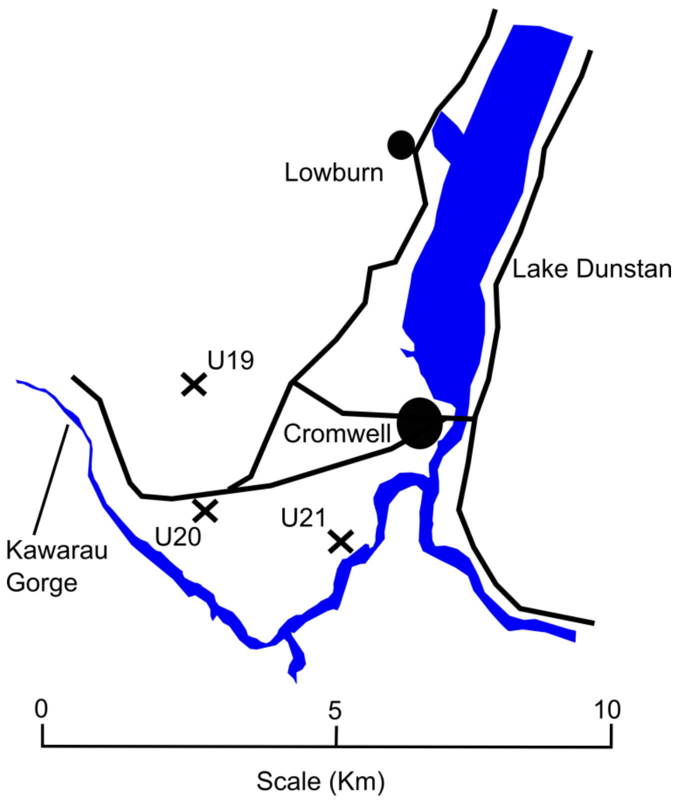


Figure 4.1 - Map of Cromwell showing locations from where samples were collected for Close and McCallion (1988) groundwater chemistry survey.

Cations	**Weight percentage (%)**
Calcium	**60.5**
Magnesium	**20**
Sodium	**17**
Potassium	**2**
Iron	**<1**
Manganese	**<1**
Anions	
Bicarbonate	**85**
Sulphate	**6.5**
Nitrate	**4.5**
Chloride	**3.5**

Table 4.1 – Summary of results from groundwater chemistry study of the Cromwell – Tarras basin (Close & McCallion, 1988).

Calcium concentrations for the Cromwell Flat were on average, higher than at other sites in the Cromwell – Tarras basin, by 38 g/m^3. In areas of irrigation, nitrate and magnesium concentrations were found to be elevated above samples from non – irrigated sites, with nitrate being increased from 0.8 g/m^3 in non – irrigated sites to 1.7 g/m^3 in irrigated sites.

Due to the Cromwell – Tarras basin being a semi arid environment with high evaporation and low precipitation, saline patches can form near on the surface of some soils near Cromwell (Close & McCallion, 1988). Close and McCallion (1988) suggested that irrigation on the Cromwell Flat may increase the salt concentration in the groundwater, and that large scale irrigation over a short period of time may result in leaching of salts into the groundwater system.

4.3 Chemical Sampling Programme

The hydrochemical data used in this study were collected by the Otago Regional Council over a time span ranging from June 1994 up until September 2006. A total of 17 samples were collected from a combination of 12 bores and 5 surface water sites from Lake Dunstan and its tributaries. The locations of the bores and surface water sample sites from where samples were collected are displayed in figure 4.2 and figure 4.9. The data used in this study were selected on the basis of availability from the O.R.C.

All samples were collected according to the O.R.C. Water Sampling Procedures Manual (O.R.C., 2009) and the National Protocol for State of the Environment Groundwater Sampling in New Zealand

(Institute of Geological and Nuclear Sciences, 2006). Sample sites were based on access to groundwater bores, access to rivers, and major drainage points from lakes and confluences of major water bodies. Water samples from the tributaries of Lake Dunstan were included as a comparison for the groundwater chemistry of the CTA, and to help put the hydrochemistry of the Cromwell Flat into a regional context.

All samples were analysed for the following suite of chemicals:

Major Cations

- Calcium (Ca)
- Magnesium (Mg)
- Sodium (Na)
- Potassium (K)

Major Anions

- Bicarbonate (HCO_3)
- Chloride (Cl)
- Sulphate (SO_4)
- Nitrite/Nitrate Nitrogen (NO_3-N)

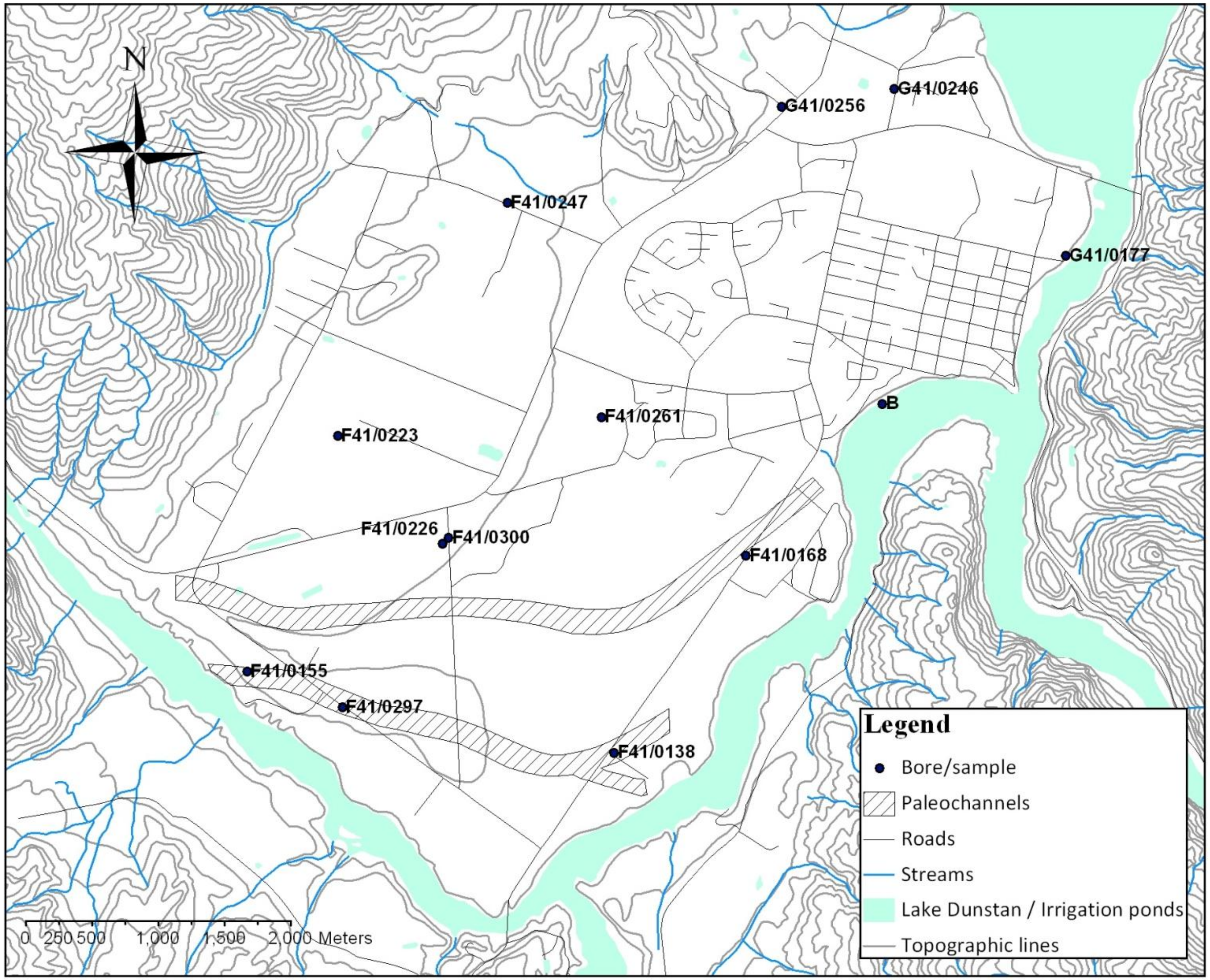
Minor Ions

- Iron (Fe)
- Ammonia Nitrogen (NH_4-N)
- Phosphorous (P)

Samples were analysed by Environmental Laboratory Services in Wellington. All but six samples were tested for pH and conductivity in the field with portable metres. Temperature was measured in the field for all but one sample.

Unfortunately, due to the large time gaps between samples for individual sites and the type of sample site, not all chemical constituents and parameters were analysed. In December 2003, the O.R.C. carried out a large water chemistry sampling program for many of the bores on the Cromwell Flat and one of the surface water sites. Where possible, water chemistry data from the December 2003 sampling program was used in this study. Samples taken from surface water bodies were all taken in 1994 and 1996, aside from one sample which was collected in 2003. The dates of collection are shown in appendix 4.3.

Figure 4.2 – Location of chemical sampling sites on the Cromwell Flat used in this study.



Purging of bores was carried out before sampling to make sure that the sample was representative of the aquifer (Jens Rekker, pers comm, 2010). A minimum of three well volumes were purged by pumping. Samples were taken as close to the well head as possible to minimise the risk of the contamination (Institute of Geological and Nuclear Sciences, 2006). For bores that had no pump, a portable pump was used.

4.4 Groundwater Chemistry Results

Results from the samples collected by the O.R.C. between June 1994 and September 2006 are shown in table 4.2. Ion balance error checks were carried out for each sample. The generally accepted ion balance error is less than 5% to ensure the validity of the data. Two samples had ion balance errors greater than 5%. These were F41/0138 (-6.5%) and F41/0297 (-6.9%). From other groundwater chemistry studies from around New Zealand, particularly in Canterbury, an ion balance error of up to 10% have been used (Abraham & Hanson, 2002). The ion balance errors of these two wells were considered to be adequate for this study.

4.5 Water Quality

4.5.1 Drinking Water Standard Comparison

The results of the samples were compared with the Drinking-water Standards for New Zealand 2005 (Revised 2008) (Ministry of Health, 2008) to evaluate water quality. This standard provides two types of criteria for drinking water. These are Guideline Values (GV's) and Maximum Acceptable Values (MAV's). GV's are based on the aesthetic qualities of the water like taste, smell and colour. MAV's are based on prevention of negative health effects to humans. A summary of the Ministry of Health (2008) GV's and MAV's are set out on appendix 4.5. The following sections compare the groundwater chemistry results from this study with the 2008 Drinking-water Standards.

4.5.2 pH

The GV for pH as outlined by the Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008) is 7 – 8.0. pH for only one sample (F41/0155, pH 6.84) transgressed this aesthetic guideline. pH across the Cromwell Flat ranges from 6.84 – to 7.8. Sample site F41/0155 is located relatively close to F41/0297 in the buried southern paleochannel, and has a pH of 7.59. Since F41/0155 is the only sample to fall below a pH of 7 and the relative abundance of carbonate material in the CTA to neutralise low pH, it is suggested that there may be some rainwater contamination which may have caused this sample to be more acidic (Vincent, 2005). The spatial distribution of pH values for sampled bores is shown in figure 4.3.

Table 4.2 – Results of Chemical sampling programme

Bore/Site	F41/0138	F41/0155	F41/0168	F41/0223	F41/0226	F41/0247	F41/0261	F41/0297	F41/0300	G41/0177
Depth (m)	37.7	42.0	35.0	45.0	-	38.5	48.6	44.8	48.8	25.0
pH	7.55^F	6.84^F	7.40^F	7.62^F	7.61^F	7.18^F	7.09^F	7.59^F	7.50^F	7.18^F
Water temperature (^oC - measured in field)	16.5	12.5	13.3	13.2	16.0	14.3	22.2	13.3	13.9	14.3
Conductivity (mS/cm)	-	-	-	-	-	-	-	-	-	-
Alkalinity to pH 8 3 (as CO_3 mg/L)	<1	<1	1.0	0.0	0.0	<1	1.0	<1	1.0	<1
Ammonia Nitrogen (mg/L)	<0.01	<0.01	<0.01	0.02	<0.005	<0.01	<0.01	<0.01	0.1	<0.01
Bicarbonate (mg/L)	138.0	292.0	196.0	330.0	260.0	259.0	288.0	131.0	260.0	148.0
Calcium (mg/L)	27.0	64.0	45.0	85.0	67.0	44.0	64.0	28.0	62.0	32.0
Chloride (mg/L)	1.5	2.7	3.7	8.5	1.3	3.5	7.2	2.7	3.0	3.3
Dissolved Reactive Phosphorus (mg/L)	<0.005	<0.005	<0.005	0.001	0.001	<0.005	<0.005	<0.005	<0.005	<0.005
Iron (mg/L)	<0.03	<0.03	<0.03	0.2	<0.05	<0.03	<0.03	<0.03	<0.03	<0.03
Magnesium (mg/L)	5.4	9.5	5.5	18.0	12.0	17.0	14.0	4.4	11.0	6.3
Nitrate-Nitrogen (mg/L)	0.2	0.1	1.5	2.2	1.0	2.8	5.3	1.4	3.4	1.3
Potassium (mg/L)	1.2	2.1	1.8	1.9	1.7	1.1	1.9	1.6	1.8	1.5
Sodium (mg/L)	6.8	4.6	10.0	20.0	4.7	15.0	16.0	6.3	4.6	8.5
Sulphate (mg/L)	5.2	9.4	6.4	55.0	7.0	10.1	19.6	7.5	7.8	9.3
Total Hardness (mg $CaCO_3$/L)**	92	203	137	294	222	187	223	90	205	108
Total Dissolved Solids (mg/L)***	186	385	271	521	355	354	417	184	355	211
Cations Total (meq/L)	2.118	2.572	3.179	6.641	4.579	4.275	5.090	2.074	4.245	2.523
Anions Total (meq/L)	2.413	2.550	3.451	6.796	4.445	4.533	5.333	2.380	4.510	2.713
Ion Balance (% diff)	-6.5	0.44	-4.1	-1.1	1.5	-2.9	-2.3	-6.9	-3.0	-3.6
Sodium absorption ratio	0.15	0.37	0.31	0.51	0.14	0.49	0.47	0.29	0.14	0.36

Notes: - No data, ^{F} - pH measured in field, ^{L} - pH measured in Lab, $^\#$ - Lab Conductivity, * - Field Conductivity, ** - Total Hardness calculated as the sum 2.5(Calcium) and 4.1(Magnesium) (Freeze, 1979), *** - Total Dissolved Solids calculated by summing ion concentrations (Fetter, 2001), **A - Lake Wanaka Outlet**, **B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D - Kawarau Bridge (Bungy), E - Lake Wakatipu (Kawarau Outlet)**

Table 4.2 – Results of Chemical sampling programme: Continued

Bore/Site	**G41/0246**	**G41/0256**	**A**	**B**	**C**	**D**	**E**
Depth (m)	37.2	32.5	Surface take	Surface take	Surface take	Surface take	Surface take
pH	7.80^L	7.41^F	7.40^L	7.50^F	7.80^L	7.20^L	7.80^L
Water temperature (^oC - measured in field)	-	13.3	15.2	15.5	2.5	7.0	2.5
Conductivity (mS/cm)	2.53$^{\#}$	-	0.061*	0.0458*	0.110*	0.070*	0.110*
Alkalinity to pH 8 3 (as CO_3 mg/L)	<2	<1	0.0	<1	-	-	-
Ammonia Nitrogen (mg/L)	-	0.01	0.02	0.01	-	-	-
Bicarbonate (mg/L)	123.0	124.0	38.0	30.0	60.0	36.0	60.0
Calcium (mg/L)	32.6	31.0	11.0	8.4	20.0	11.0	20.0
Chloride (mg/L)	2.4	1.6	0.6	0.5	0.5	0.6	0.5
Dissolved Reactive Phosphorus (mg/L)	0.0	<0.005	0.001	<0.005	-	0.001	-
Iron (mg/L)	<0.005	<0.03	-	<0.03	-	-	-
Magnesium (mg/L)	5.7	2.4	0.5	0.5	1.4	0.8	1.4
Nitrate-Nitrogen (mg/L)	0.6	0.2	0.03	0.03	0.04	0.04	0.04
Potassium (mg/L)	1.1	1.0	0.7	0.7	0.7	0.5	0.7
Sodium (mg/L)	8.1	5.1	0.8	2.3	1.7	1.4	1.7
Sulphate (mg/L)	5.2	5.0	3.1	4.6	7.1	5.0	7.1
Total Hardness (mg $CaCO_3$/L)**	105	87	30	23	56	31	56
Total Dissolved Solids (mg/L)***	181	171	55	48	91	55	91
Cations Total (meq/L)	2.478	1.992	0.643	0.578	1.205	0.688	0.594
Anions Total (meq/L)	2.292	2.182	0.705	0.602	1.146	0.711	0.565
Ion Balance (% diff)	3.9	-4.6	-4.6	-2.0	2.5	-1.6	2.5
Sodium absorption ratio	0.34	0.24	0.11	0.13	0.10	0.21	0.06

Notes: - No data, ^{F} - pH measured in field, ^{L} - pH measured in Lab, $^{\#}$ - Lab Conductivity, * - Field Conductivity, ** - Total Hardness calculated as the sum 2.5(Calcium) and 4.1(Magnesium) (Freeze, 1979), *** - Total Dissolved Solids calculated by summing ion concentrations (Fetter, 2001), **A - Lake Wanaka Outlet**, **B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D - Kawarau bridge (Bungy), E - Lake Wakatipu (Kawarau outlet)**

Figure 4.3 – Distribution of pH for sampled bores and lake sample B.

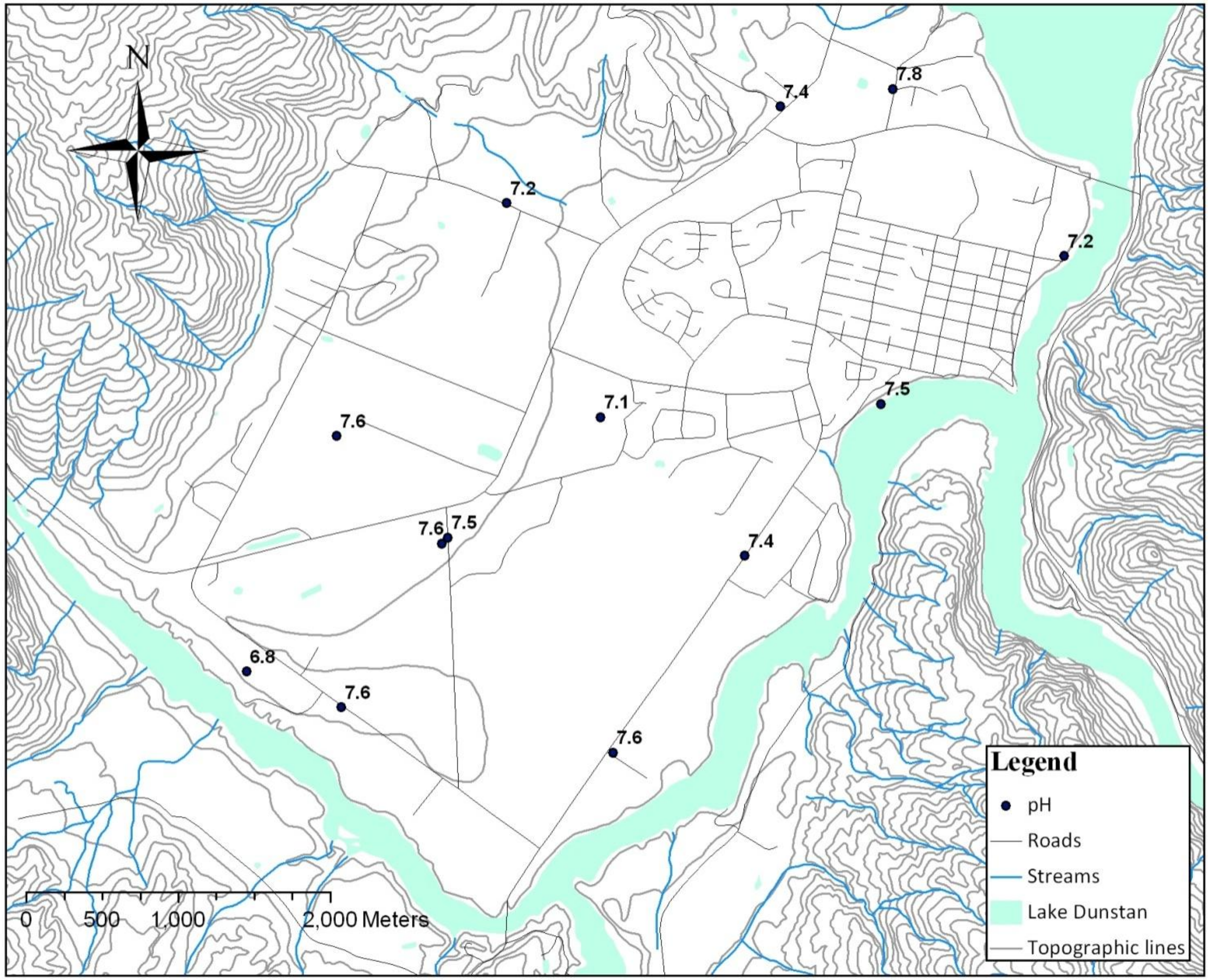
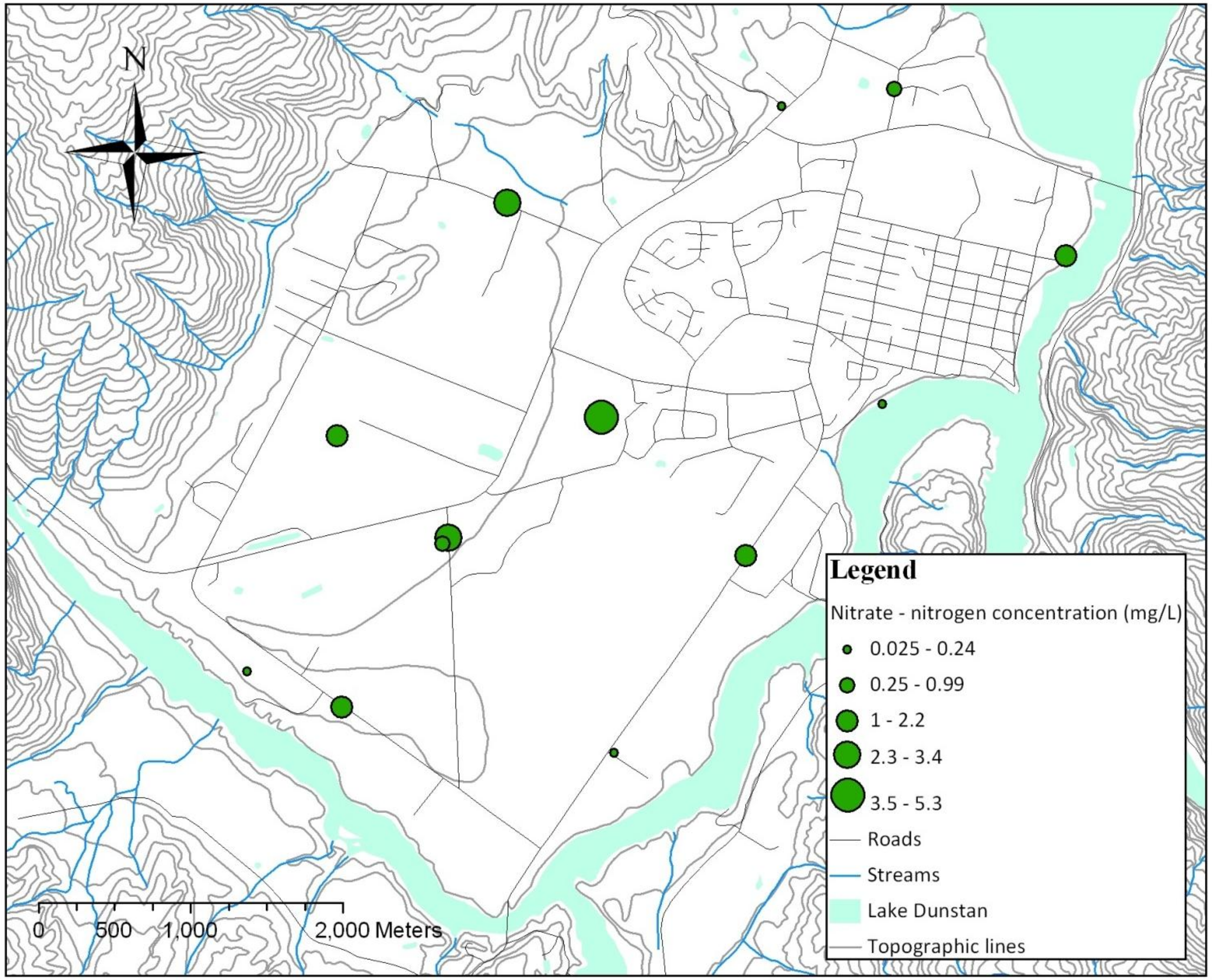


Figure 4.4 – Distribution of nitrate – nitrogen for sampled bores and lake sample B.



4.5.3 Nitrate – Nitrogen

The Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008) MAV for nitrate – nitrogen is 11.3 mg/L. No samples transgressed this maximum acceptable value, with all samples ranging between 0.1 and 5.3 mg/L. Figure 4.4 shows the spatial distribution of the nitrate-nitrogen concentrations from the sampled bores. The higher concentrations seem to be clustered around the middle and western side of the Flat with lower concentrations around the lake margin.

Nitrate-nitrogen occurs naturally in groundwater although it is generally in low concentrations. Concentrations of nitrate-nitrogen greater than 3 mg/L are suggested to be the result of contamination from anthropomorphic sources such as stock effluent, waste disposal or fertiliser application (Madison & Brunett, 1985). Only two samples exceeded this natural nitrate-nitrogen concentration of 3 mg/L. These were F41/0300 (3.4 mg/L) and F41/0261 (5.3 mg/L). F41/0300 is located on land converted from farm land to a vineyard. Fertiliser application on the vineyard would be the likely cause for the slightly elevated nitrate-nitrogen concentrations. F41/0261 is located at the Cromwell Sale yards, with the likely source of nitrate-nitrogen being from livestock effluent.

4.5.4 Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) gives a basic measure of water quality and is the total amount of solid material in mg/L that remains after a water sample has been evaporated to dryness (Freeze & Cherry, 1979). Water can be classed under four different classes depending on the amount of TDS. These classes are shown in table 4.2.

Class	TDS (mg/L)
Fresh water	0 -1,000
Brackish water	1,000 – 10,000
Saline water	10,000 – 100,000
Brine Water	>100,000

Table 4.3 – Groundwater Total Dissolved Solids Classification (from Fetter 2005)

Figure 4.5 shows the spatial distribution of TDS on the Cromwell Flat. All samples fall into the fresh water category with samples ranging from 171 – 521 mg/L. Figure 4.4 shows that the TDS decreases out toward the of the edge of the terrace. This decrease is likely to be either from mixing of surface precipitation percolating downward from the terrace surface or mixing with water infiltrating into the aquifer from Lake Dunstan.

4.5.5 Total Hardness

Total Hardness or Calcium + Magnesium hardness is a measure of quantity of calcium and magnesium in the water (Hem, 1992). A basic definition of hard or soft water is the ability in which soap can be lathered in a particular water. In hard water, soap is difficult to lather, but in soft water it is easily lathered (Vincent, 2005). Total hardness of water can be classified under four classes depending on the concentration of $CaCO_3$ in mg/L. These classes are soft, moderately hard, hard and very hard (table 4.4).

Class	**Hardness range (mg/L of $CaCO_3$)**
Soft	0 – 60
Moderately hard	61 – 120
Hard	121 – 180
Very hard	>180

Table 4.4 – Classification scheme for Total Hardness (Hem, 1992).

The spatial distribution of total hardness is shown in figure 4.6. Most waters can be described as moderately hard to hard waters with samples from the interior of the Cromwell flat being very hard. Groundwaters in Central Otago are generally calcium carbonate rich due to calcite being a common secondary mineral in the Otago Schist (Coombs et al, 1985; Rosen et al, 1997). Samples from around the edge of the Cromwell Flat have a hardness range between 87 – 203 mg/L of $CaCO_3$ whereas samples from the interior of the Cromwell Flat range between 187 – 294 mg/L of $CaCO_3$.

Hardness of water doesn't pose any health risks but can lead to build up of scum or scale inside pipes, electric kettles and dishwashers as some residents of the Cromwell Flat have experienced. Build up of lime scale is common when using groundwater extracted from most bores across the Cromwell Flat.

4.5.6 Cations

Figure 4.7 shows the relative concentrations of the major cations, presented as pie charts in milliequivalents per litre (meq/L). Calcium is the dominant cation with both magnesium and sodium having relatively high concentrations as well. Potassium has low concentrations in all samples. This is due to the ability of potassium to be easily removed out of solution during reactions in the aquifer or soil matrix (Rosen, 2001). Concentrations of cations are higher in the centre of the terrace with concentrations decreasing toward the lake margin. The highest concentrations of cations are in samples F41/0223 and F41/0261 which both had the highest TDS and Total Hardness values. F41/0261 also had the highest nitrate – nitrogen count for all of the samples as well. The cation

Figure 4.5 – Distribution of total dissolved solids for sampled bores and lake sample B.

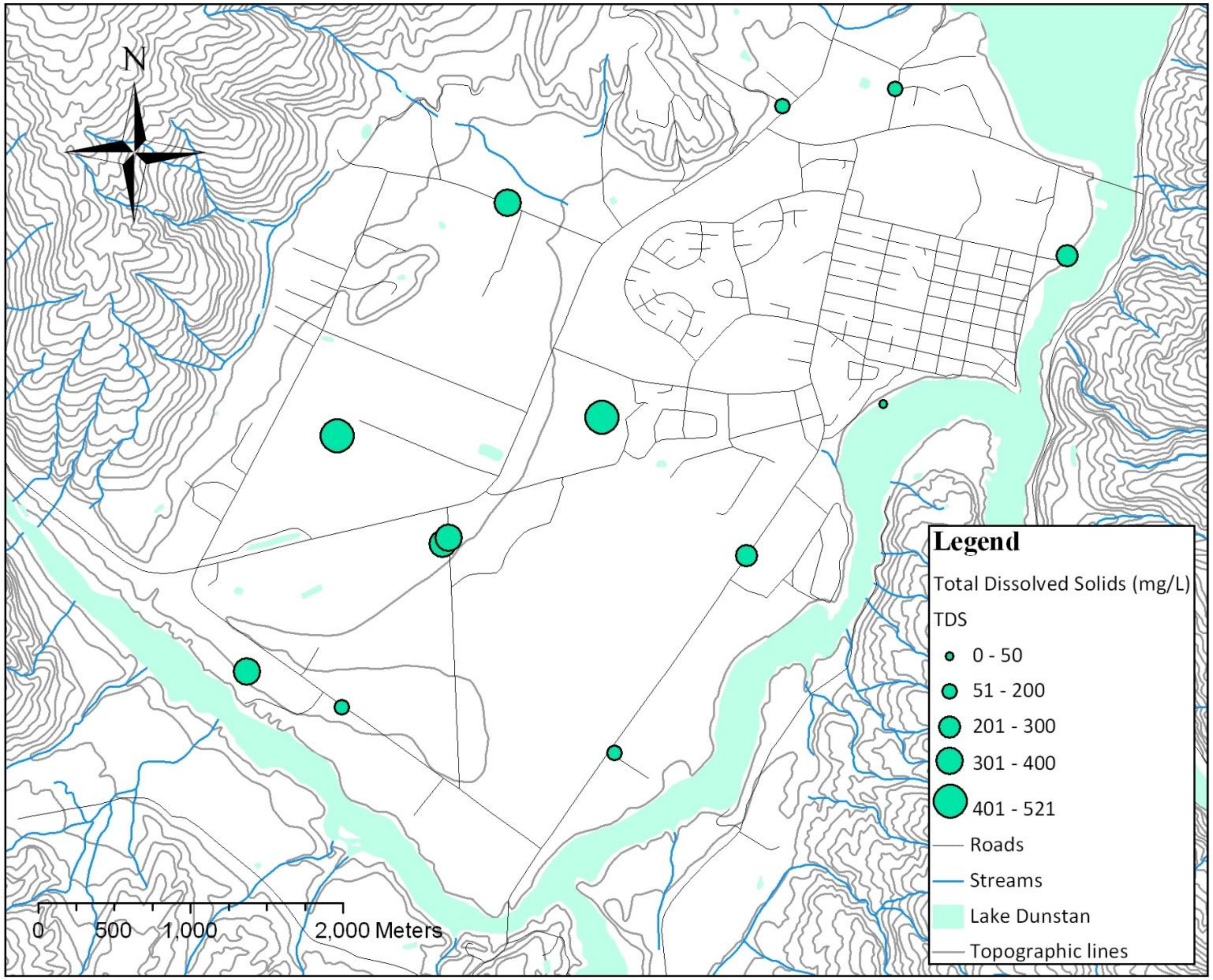


Figure 4.6 – Distribution of hardness for sampled bores and lake sample B.

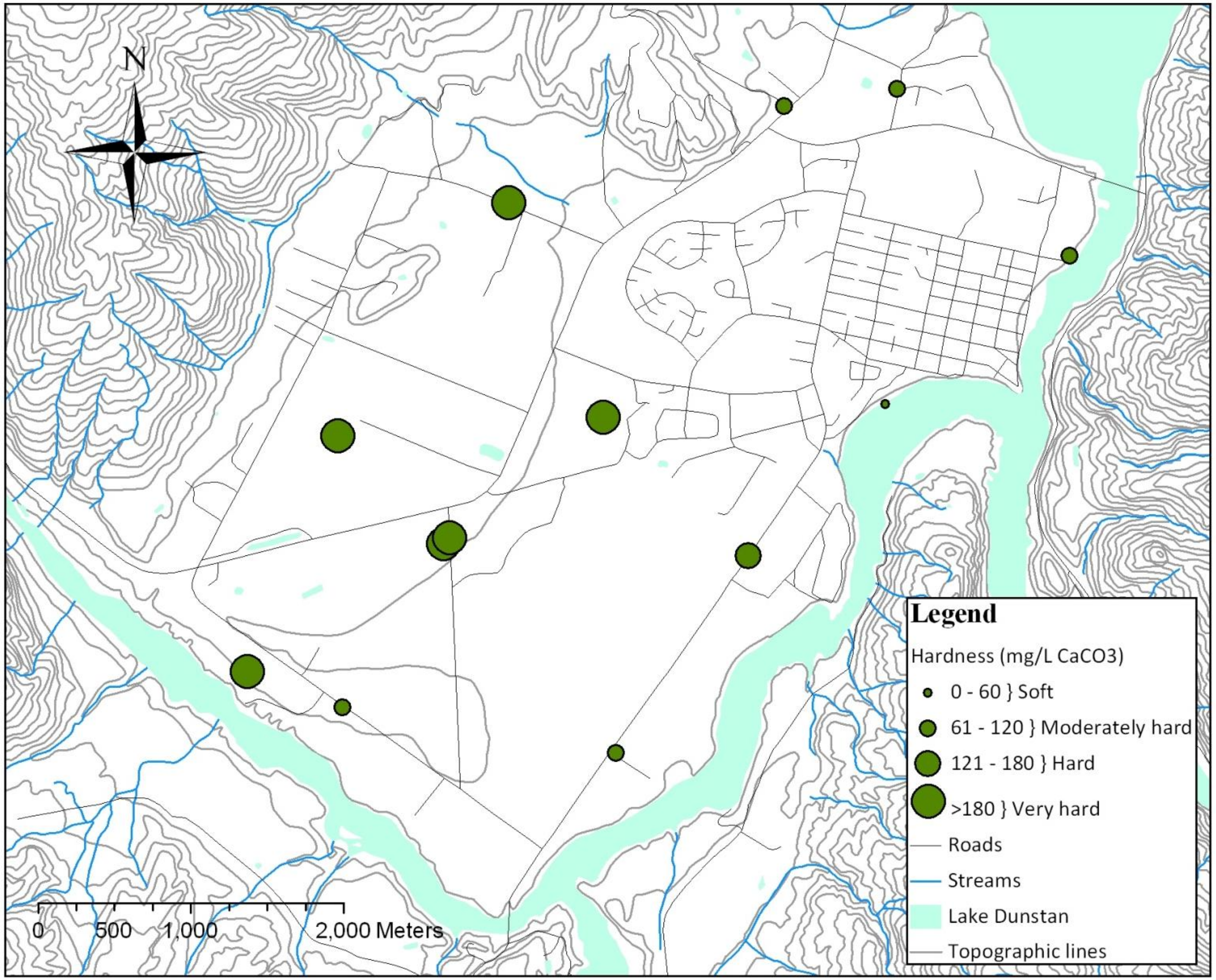


Figure 4.7 – Pie charts showing the relative abundance of cations (in meq/L) for sampled bores and lake sample B.

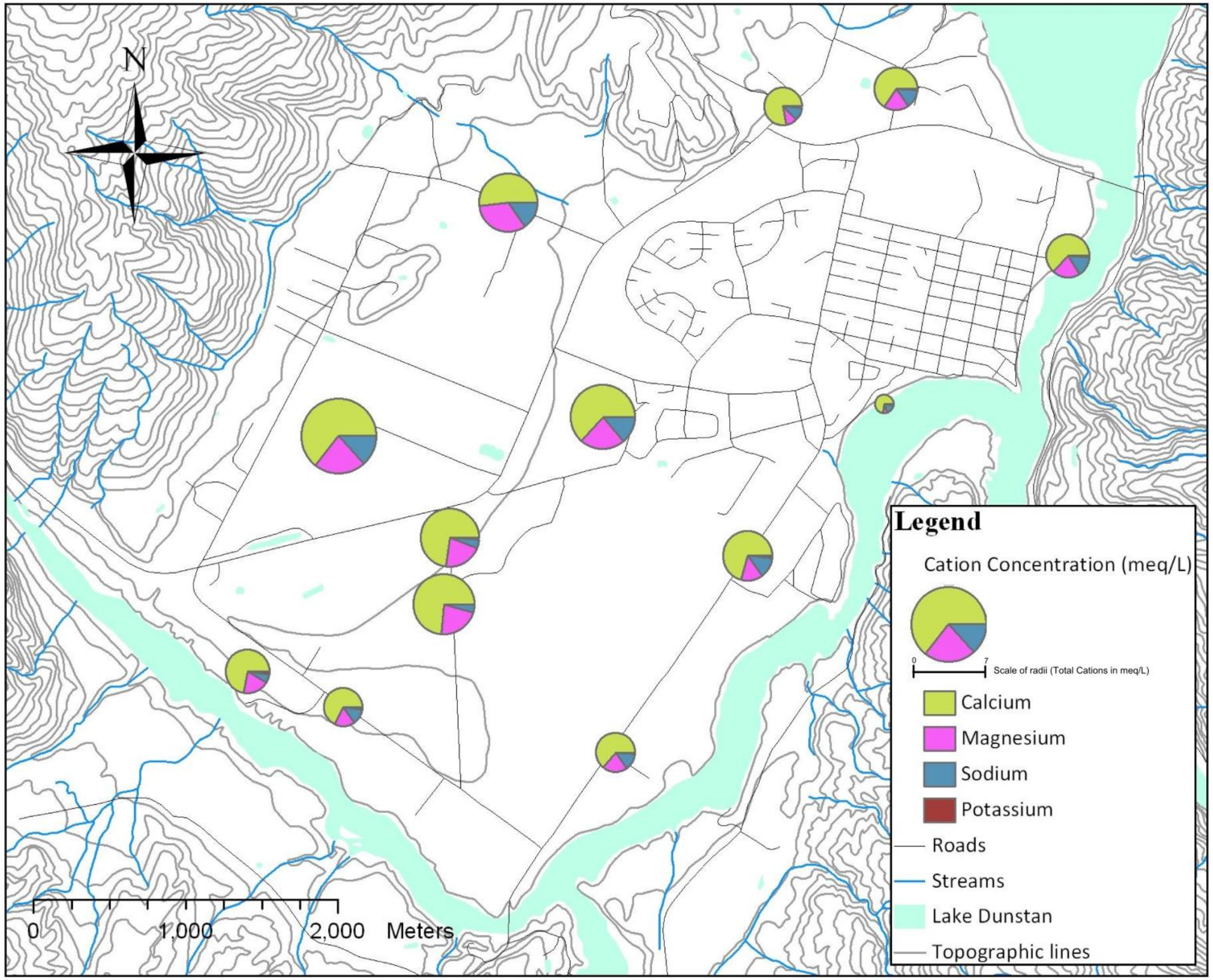
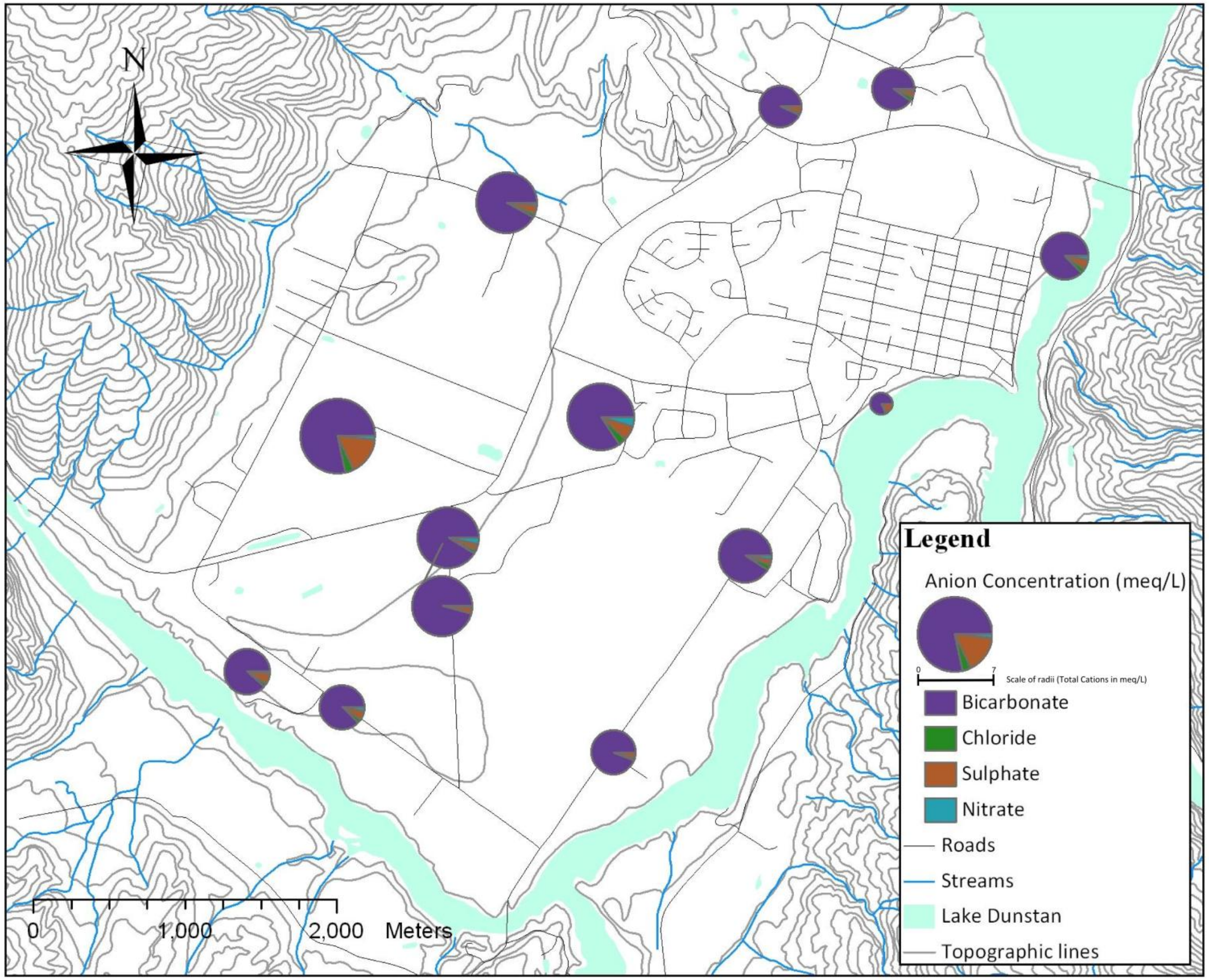


Figure 4.8 – Pie charts showing the relative abundance of anions (in meq/L) for sampled bores and lake sample B.



concentrations for each sample is shown in figure 4.7 and table 4.1.

4.5.7 Anions

The relative concentrations of the major anions, meq/L, are shown in figure 4.8. Bicarbonate is the dominant anion in all samples, with only small concentrations of sulphate, chloride and nitrate. According to Chebotarev (1955), anion concentrations in groundwaters typically evolve from young, shallow, bicarbonate rich waters to deeper, older chloride rich waters. This evolution is known as the Chebotarev sequence and is displayed in figure 4.9.

Travel along flow path $\longrightarrow$

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

Increasing age $\longrightarrow$

Figure 4.9 - Chebotarev sequence displaying the chemical evolution of anions through a groundwater system (Freeze & Cherry, 1979).

The sequence relies on 3 factors for completion: age of the water, travel time and solubility and availability of the particular minerals in the groundwater system (Chebotarev, 1955).

Typically in New Zealand, groundwater doesn't evolve past the bicarbonate stage due to a lack of soluble minerals (Rosen, 2001). This has been observed in the Canterbury plains aquifer systems due to them being composed of greywacke gravels which is mostly made up of silica and is insoluble (Vincent, 2005). The Otago Schist in the Cromwell area is essentially metamorphosed greywacke and has a similar composition and the bicarbonate dominance in the CTA reflects this. The aquifer is also shallow, unconfined and relatively small which would further restrict evolution of groundwater, due to potential surface water mixing and short travel time in the aquifer.

The total anion concentrations are shown in figure 4.8 and table 4.1. They mirror those of the cations, with higher concentrations in the interior of the terrace, and lower concentrations toward the lake margin.

4.5.8 Total Dissolved Reactive Phosphorus

Total Dissolved Reactive Phosphorus is the measure of phosphate in the water sample. Phosphorus is a relatively common element in the earth's crust but doesn't typically occur in high concentrations in groundwater or surface water (Hem, 1992; Tue – Nugen et al., 2005). The concentration of phosphate in natural waters is typically 0.01 (mg/L) and in New Zealand, natural phosphate concentrations are typically 0.03mg/L (Hem, 1992; Rosen, 2001). Due to the low concentrations of phosphorus in groundwater and surface water bodies, there is no MAV or GV for it in the Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008). Phosphorus rich waters can indicate contamination from sewerage or phosphate rich fertilisers (Hem, 1992).

Concentrations of phosphorus in the samples ranged from 0.001 – 0.005 mg/L, much less than the naturally occurring concentrations outlined by Hem (1992).

4.5.9 Iron

The Ministry of Health Drinking-water Standards for New Zealand 2005 (Revised 2008) (2008) GV for iron is 0.2 mg/L. At concentrations higher than this, staining of sanitary and laundry ware can become an issue (Ministry of Health, 2008). All samples, except F41/0223, had Iron concentrations well below the GV. The iron concentration for sample F41/0223 matched the GV of 0.2mg/L (Table 4.1). The low concentrations of iron, along with low concentrations of ammonia nitrogen, suggest that the aquifer is an oxygen rich environment (Vincent, 2005).

4.5.10 Sodium Absorption Ratio (SAR)

The sodium absorption ratio is used as a means of evaluating groundwater for its suitability for irrigation. The sodium absorption ratio is calculated via the following equation:

$$SAR = \frac{(Na+)}{\left(\frac{(Ca^{2+}) + (Mg^{2+})}{2}\right)^{0.5}}$$

where sodium, calcium and magnesium are in milliequivalents per litre (meq/L) (Fetter, 2001).

Water used for irrigation, that is high in sodium and low in calcium, results in part of the sodium being taken up by clay in the soil. Sodium is taken up in the structure of the clay particle in exchange for calcium and magnesium. This exchange can result in the destruction of the soil structure due the clay particles being dispersed (Fetter, 2001). This cause the salinity of the soil to increase and inhibit plant growth, leaving the soil barren (Seilsepour & Rashidi, 2008).

Sodium absorption ratio	Irrigation hazard from sodium
0 – 10 (<2 more favourable)	Little danger (good irrigation water)
7 – 18	Medium danger
11 – 16	High danger
>26	Very high danger (bad irrigation water)

Table 4.5 – Sodium Absorption Ratio and irrigation classification scheme (Fetter, 2001; Vincent, 2005)

The SAR for all samples was less than 1. This indicates that groundwater on the Cromwell Flat is of good quality and there is little danger from sodium.

4.6 Lake Dunstan and Tributaries

Figure 4.10 shows the locations of the 5 lake water and river water samples that were analyzed. These samples were analyzed as they are part of Lake Dunstan or supply water to Lake Dunstan. These samples help to put the water chemistry of the CTA into a regional context. Three of these samples were collected from open water bodies (lakes) and two were collected from major rivers.

Table 4.1 shows the results of the analysis of these samples. All of quantities of the major cations and anions analyzed are significantly lower than that of the CTA samples. This is most notable in the total cations and anions with samples from Lake Dunstan and its tributaries having values ranging from 0.6 to 1.2meq/L. All of the samples from the CTA had values ranging from 2.0 to 6.8meq/L. One useful method of showing the difference in the total amount of cations and anions of between water types is to plot the sum of the cationic charge ($Tz^+ = 2[Mg^{2+}] + [Ca^{2+}] + [K^+] + [Na^+]$) versus the sum of anionic charge ($Tz^- = 2[SO_4^{2-}] + [HCO_3^-] + [Cl^-]$) in microequivalents per litre (µeq/L) (Horton et al, 1999). A plot of this is displayed in figure 4.11. The samples from Lake Dunstan and its tributaries all cluster together on this plot where as samples from the CTA are more spread out. Sample C is the only exception as it has a slightly higher cationic and anionic sum than the other samples Lake Dunstan and tributaries but is still significantly lower than the CTA samples.

The reason for the lower cationic and anionic sum is likely to be due to mixing of rainwater. Since all of these samples were collected from lakes or major rivers, mixing with rain water is inevitable. Rainwater typically has very low amounts of dissolved ions and dilutes ionic rich water (Freeze & Cherry, 1979). This results in lower cationic and anionic sums, as observed from these samples. The lower cationic and anionic sum of the samples from Lake Dunstan and its tributaries compared with the samples from the CTA indicate that Lake Dunstan isn't the source of recharge to the aquifer. However, there may be some mixing of lake water with groundwater along the lake margin which may explain the large spread of the CTA bore sample cationic and anionic sum data.

No samples from Lake Dunstan and its tributaries breached any MAV or GV set out by the Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008).

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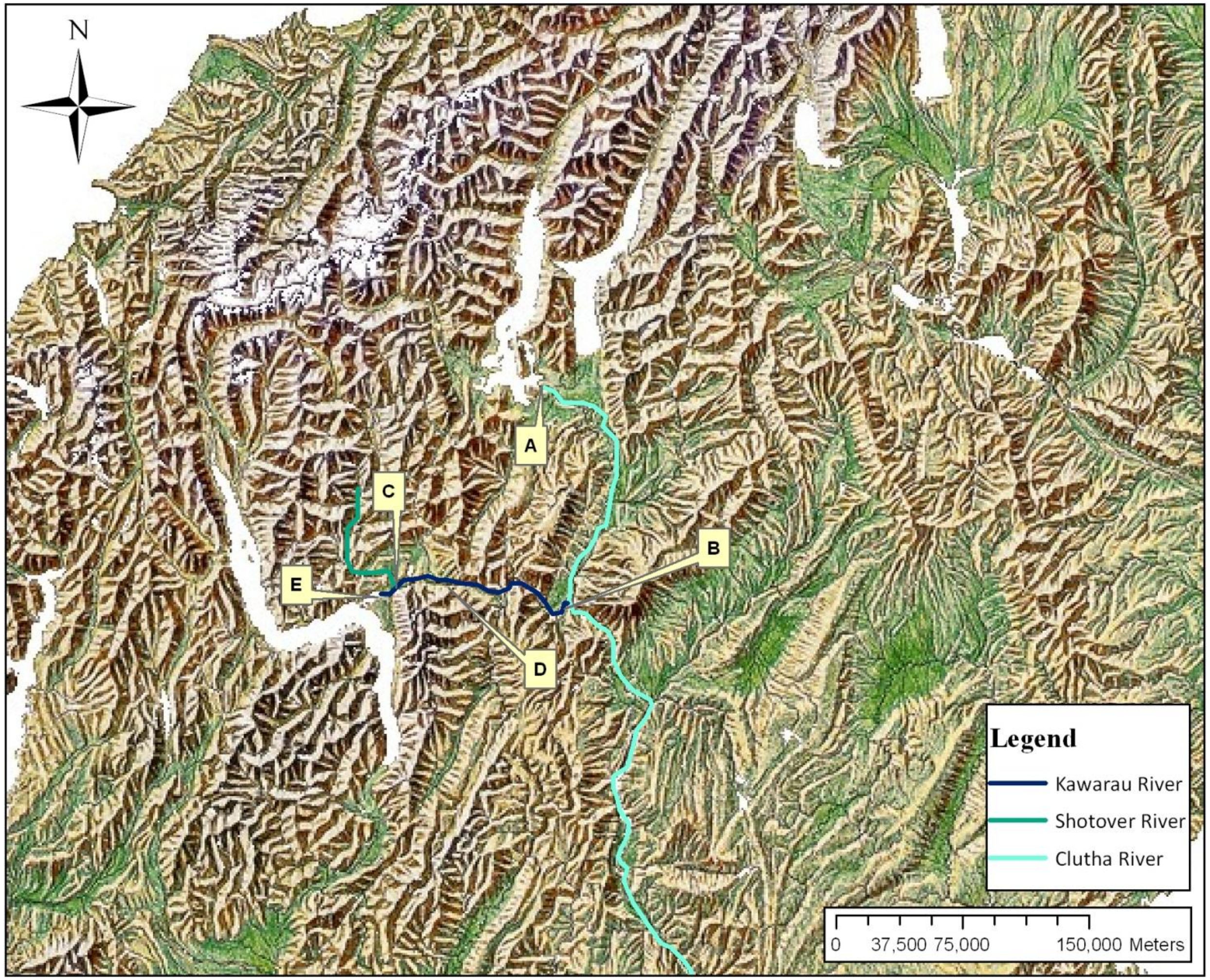
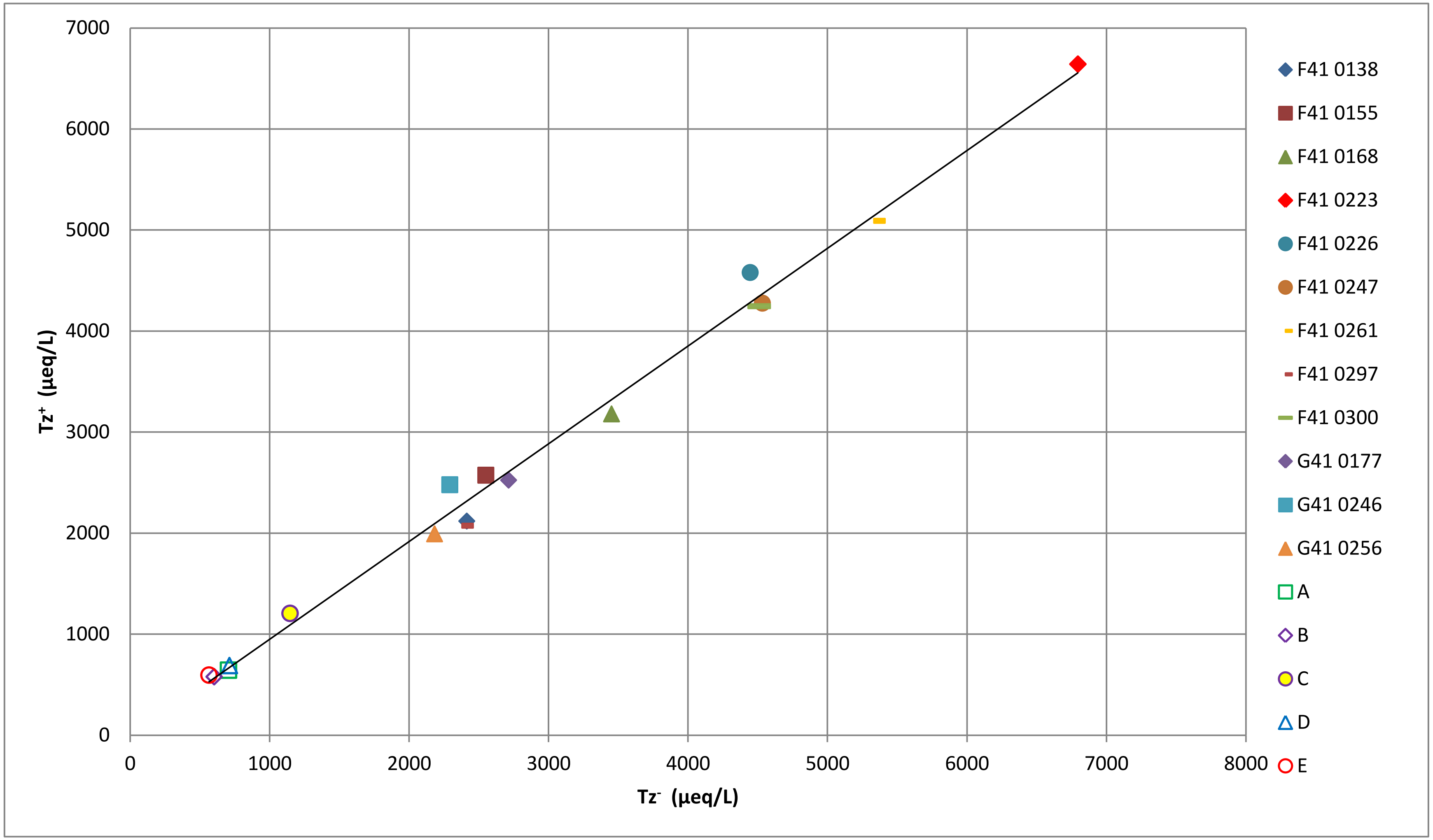
Figure 4.10 – Map showing locations from where chemical samples for Lake Dunstan and its tributaries were collected.



Notes: A - Lake Wanaka Outlet, B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D Kawarau Bridge (Bungy), E - Lake Wakatipu (Kawarau outlet)

Figure 4.11 – Plot of sum of base cationic charge (Tz^+; µeq/L) versus anionic charge (Tz^-; µeq/L) for chemical samples from the CTA and Lake Dunstan and its tributaries.



Notes: Sum of cationic charge (Tz^+; µeq/L) = ($Tz^+ = 2[Mg^{2+}] + 2[Ca^{2+}] + [K^+] + [Na^+]$); and sum of anionic charge(Tz^-; µeq/L) = ($Tz^- = 2[SO_4^{2-}] + [HCO_3^-] + [Cl^-]$)

4.7 Groundwater Classification

4.7.1 Graphical Presentation of Chemical Analyses

The results of the chemical analyses of all samples were graphically presented in Stiff Patterns (Stiff, 1951) and Piper diagrams (Piper, 1944) to help distinguish hydrochemical facies in the groundwater and the surrounding waters of Lake Dunstan. These two types of graphical presentation were used as they are the most common methods of graphical analysis for studying groundwater used by Hydrogeologists.

4.7.2 Methodology and Application of Piper diagrams

Piper (1944) developed a trilinear or Piper diagram that can be used to find the specific hydrochemical facies of numerous samples. Piper diagrams allow multiple samples to be plotted together on a single plot. Piper diagrams can also help in identifying whether a specific water type is the product of mixing of waters. Figure 4.12 C shows an example of a Piper diagram. Piper diagrams use the most common major ionic species found in the majority of natural water and display the composition of the three ions as a percentage. These ionic species are Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, SO_4^{-}, HCO_3^{-}, Cl^{-}, and CO_3^{-} which are plotted on a trilinear diagram. The trilinear diagram has 2 triangular plotting fields for the cations and anions, and a diamond shaped field that has each side of it represented by a pair of cations and anions. The sides of each field has a scale of 0 to 100 as analysis of the water samples plot each anion and cation as a percentage Na and K are grouped together, along with HCO_3 and CO_3, so the groups of major cations and anions can be displayed on the trilinear diagram.

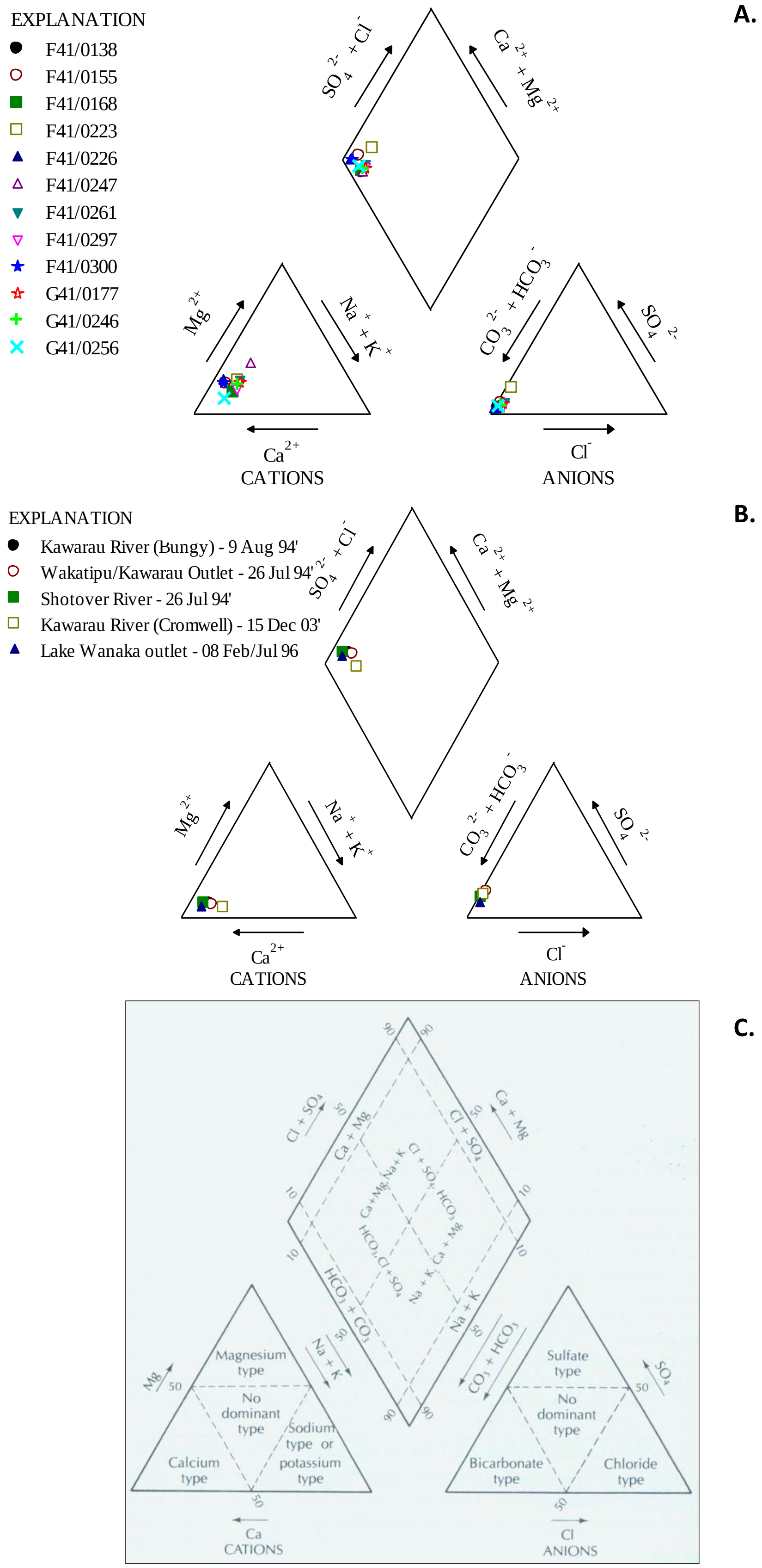
The cations and anions are plotted in their respective triangular fields as a single point, and are then both projected up into the diamond shaped field. Where the two projected points intersect in the diamond shaped field, a point can be plotted, indicating the water type.

Figures 4.12 A and B show the water chemistry data from Cromwell Flat bores and Lake Dunstan and its tributaries presented on Piper diagrams. Both diagrams show that all waters from are of the calcium bicarbonate type.

4.7.3 Methodology and Application of Stiff Patterns

Stiff Patterns are constructed by displaying major cation/anion pairs (i.e. Mg – SO_4; Ca – HCO_3, and Na + K - Cl) on their own individual horizontal axes, with all major cations on one side and anions on the other (Stiff, 1951). A vertical axis divides the anions from the cations, and acts as zero for each of

Figure 4.12 – Piper diagram for samples from bores on Cromwell Flat (A.) and Lake Dunstan and its Tributaries (B.). C. Shows the hydrochemical classification scheme for the Piper diagram from Fetter (2001).



the horizontal axes. Data for each ionic concentration are plotted on the corresponding horizontal axis in units of milliequivalents per litre. The resulting points are then linked to produce a polygonal shape that will be indicative of that specific water sample. Stiff Patterns display the concentrations of the major ions in an individual water sample visually, so it can be compared to other water samples.

Classification of groundwater using the Stiff Pattern depends on the dominant cation and anion pair. This methodology works for the majority of Stiff Patterns but some patterns may display relative ionic concentrations that are even or close to even. In this case, no dominant water type can be determined. Patterns that show no dominant water type are generally evolving due to the mixing of different waters (Vincent, 2005).

A general rule proposed by Hem (1992) states that the relative anion and cation concentrations need to have a difference of at least 50%. If not, then no classification should be used.

4.7.3.1 Stiff Patterns and hydrochemical Facies

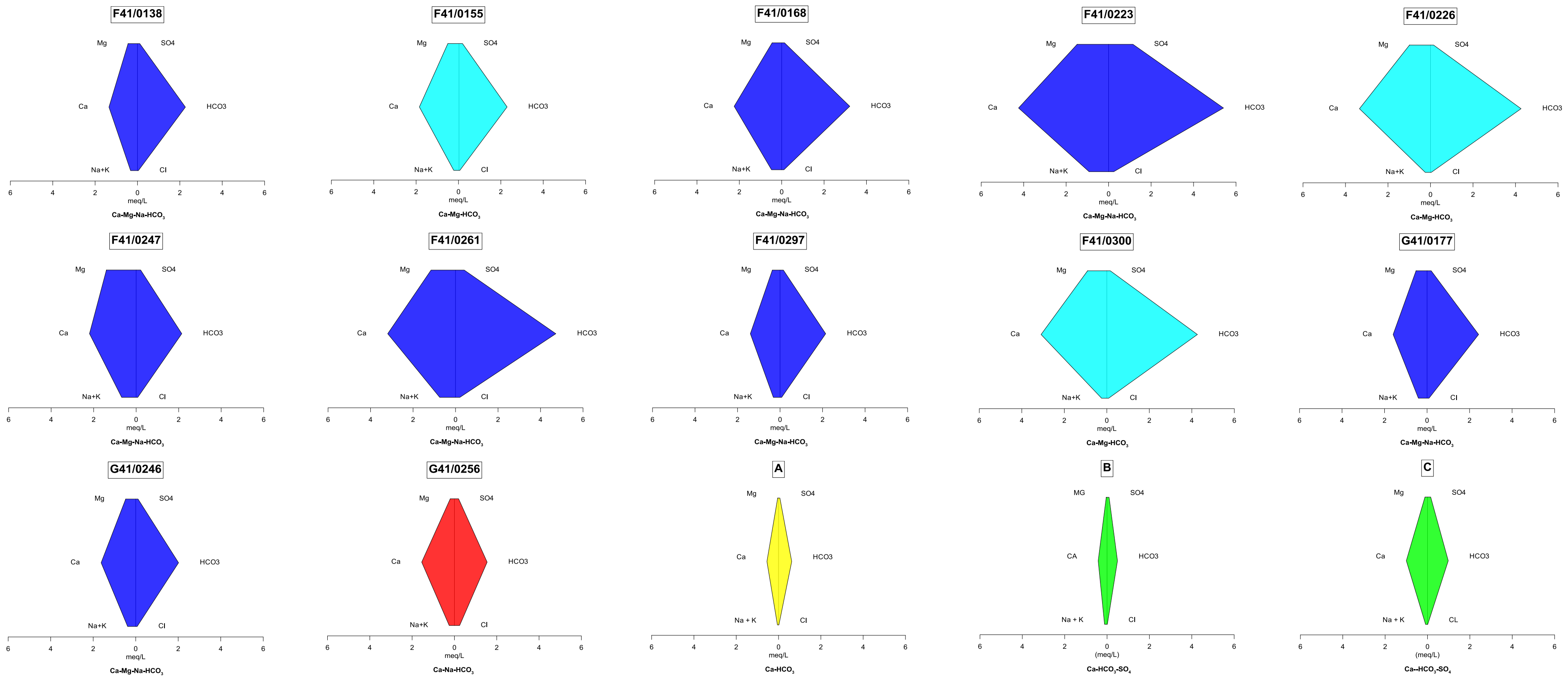
Stiff plots for all water samples collected are shown in figure 4.13 and in plan view in figure 4.14. Each stiff diagram was assigned a particular colour based on its hydrochemical signature. The hydrochemical signature for each stiff diagram was found using the 'equivalents method' described by Rosen (2001). In this method, the major cations (Ca, Mg, Na, K) and anions (HCO_3, CO_3, Cl, SO_4)

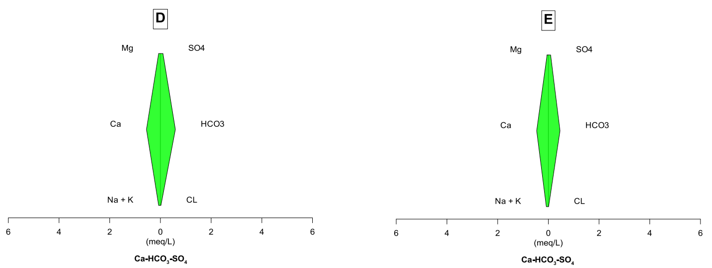
Stiff plot colour	Bore number/lake sample	Hydrochemical signature
Dark Blue	F41/0138, F41/0168, F41/0223 F41/0247, F41/0261, F41/0297, G41/0177, G41/0246	Ca-Mg-Na-HCO_3
Light blue	F41/0226, F41/0300, F41/0155	Ca-Mg-HCO_3
Red	G41/0256	Ca-Na-HCO_3
Green	B, C, D, E	Ca-HCO_3-SO_4
Yellow	A	Ca-HCO_3

Table 4.6 – Differentiation of CTA groundwater samples and lake water samples into groups based on hydrochemical signature using the 'equivalents method' by Rosen (2001).

have their weights converted from milliequivalent per litre (meq/L) to percentages (appendix 4.7). The hydrochemical facies are described by listing the ions greater than 10% in decreasing order, starting with the cations (Rosen, 2001). Table 4.6 shows the five different hydrochemical facies that ground water and lake water can be divided into. All samples are dominated by the major cation/anion pair of calcium and bicarbonate.

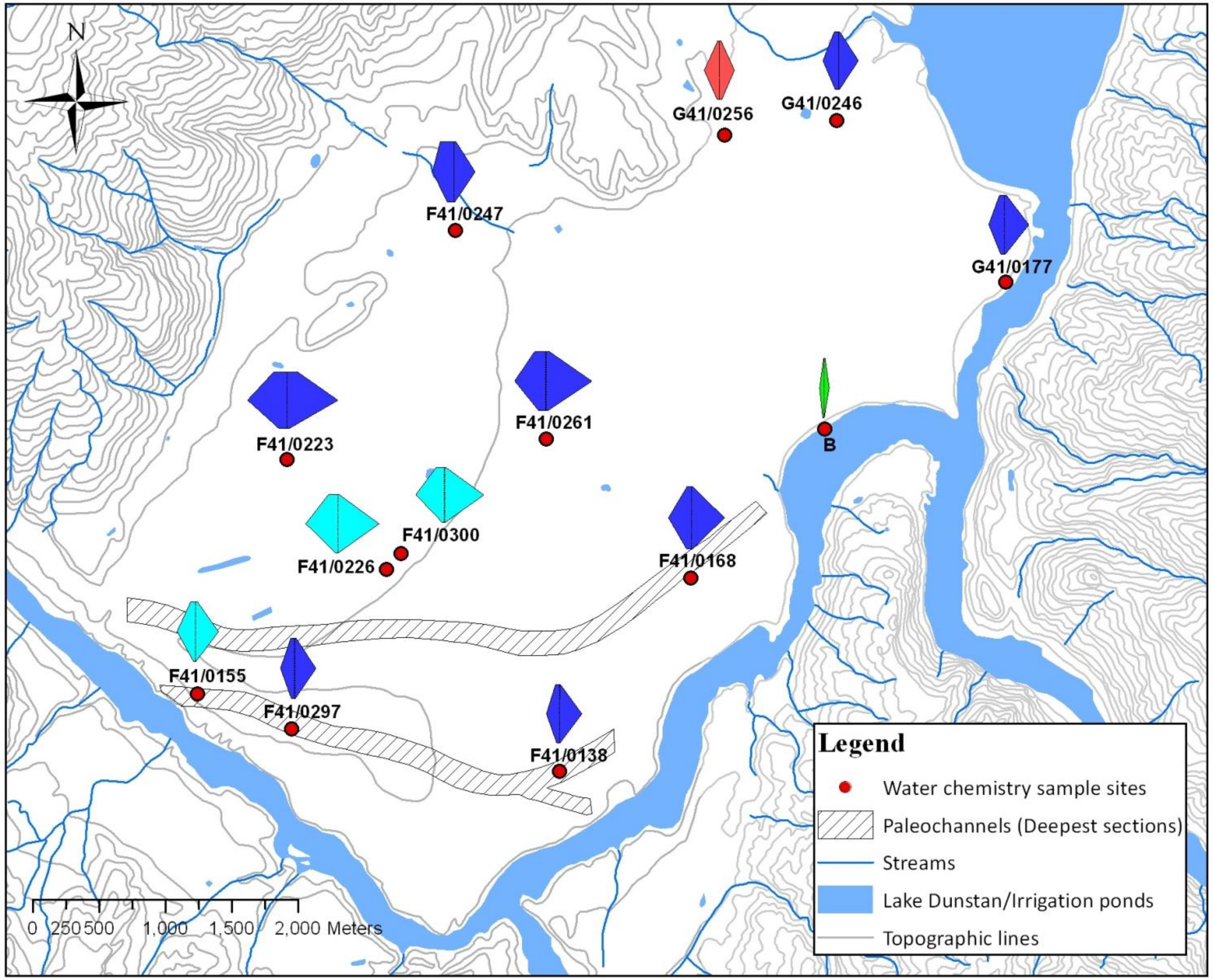
Figure 4.13 – Stiff patterns for sampled bores and Lake Dunstan and its tributaries





Notes: A - Lake Wanaka Outlet, B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D Kawarau Bridge (Bungy), E - Lake Wakatipu (Kawarau outlet)

Figure 4.14 – Map showing distribution of stiff plot patterns for sampled bores and lake sample B.



The dark blue colour is the most common hydrochemical signature with Mg and Na. Samples have high to medium ionic concentrations and are scattered across the terrace. The light blue samples have Mg and are localised to the south west end of the terrace. They have high to medium ionic concentrations. The single red stiff diagram is characterised by Na, and is located at the entrance to the Burns Cottage Rd. Valley. The single yellow and green samples all have medium to low ionic concentrations. The greens sample are characterised by SO_4 where the yellow sample is characterised only by Ca and HCO_3.

In general all of the stiff diagrams have a very similar shape that only really differ in size, or the concentration of calcium and bicarbonate. The stiff diagrams in the interior of the Cromwell Flat are generally larger or have higher concentrations of calcium and bicarbonate than the diagrams nearer the edge of the lake. Since the overall shape remains similar, and the ionic concentrations of calcium and bicarbonate decrease, it can be suggested that mixing with rainwater is occurring as groundwater flows outward from the Pisa Range toward Lake Dunstan. Rainwater is slightly acidic and reacts with calcium carbonate, effectively reducing the Ca and HCO_3 concentrations in the groundwater (Freeze & Cherry, 1979).

Alternatively, the smaller size of the stiff diagrams nearer the lake margin maybe due to mixing of lake water that has infiltrated into the aquifer. The stiff diagrams for the lake water samples also display the same shape but have significantly lower ionic concentrations. Since annual evaporation on the Cromwell Flat is nearly 3 times the annual precipitation, it would be more plausible for there to be mixing of lake water in the aquifer rather than precipitation infiltrating down from the surface.

4.8 Stable Isotopic Analysis

4.8.1 Methodology

Stable isotopic analysis of surface water, groundwater and precipitation using ^{18}O and ^{2}H was carried out to try and distinguish the different water types in the Cromwell area.

Water molecules are made up of two hydrogen atoms to one oxygen atom. Both hydrogen and oxygen occur naturally as a number of different stable isotopes. Hydrogen has 2 common stable isotopes of ^{1}H and ^{2}H (Deuterium) which have mass abundances in the hydrosphere of 99.985% and 0.015% respectively (Gat, 2010). Oxygen has 3 naturally occurring stable isotopes, ^{16}O, ^{17}O and ^{18}O with abundances of 99.762%, 0.0379% and 0.200% respectively. ^{16}O and ^{18}O are normally used, as they are more common in the hydrosphere than ^{17}O (Gat, 2010).

Isotopic tracing of the hydrologic cycling is facilitated by the different masses of the isotopic species. Due to ^{18}O having a higher atomic mass than ^{16}O, ^{18}O fractionates relative to the lighter ^{16}O during evaporation or condensation events (Sharp, 2007). This results in either more ^{18}O depleted water (condensation) or more ^{18}O enriched water (evaporation) (Sharp, 2007).

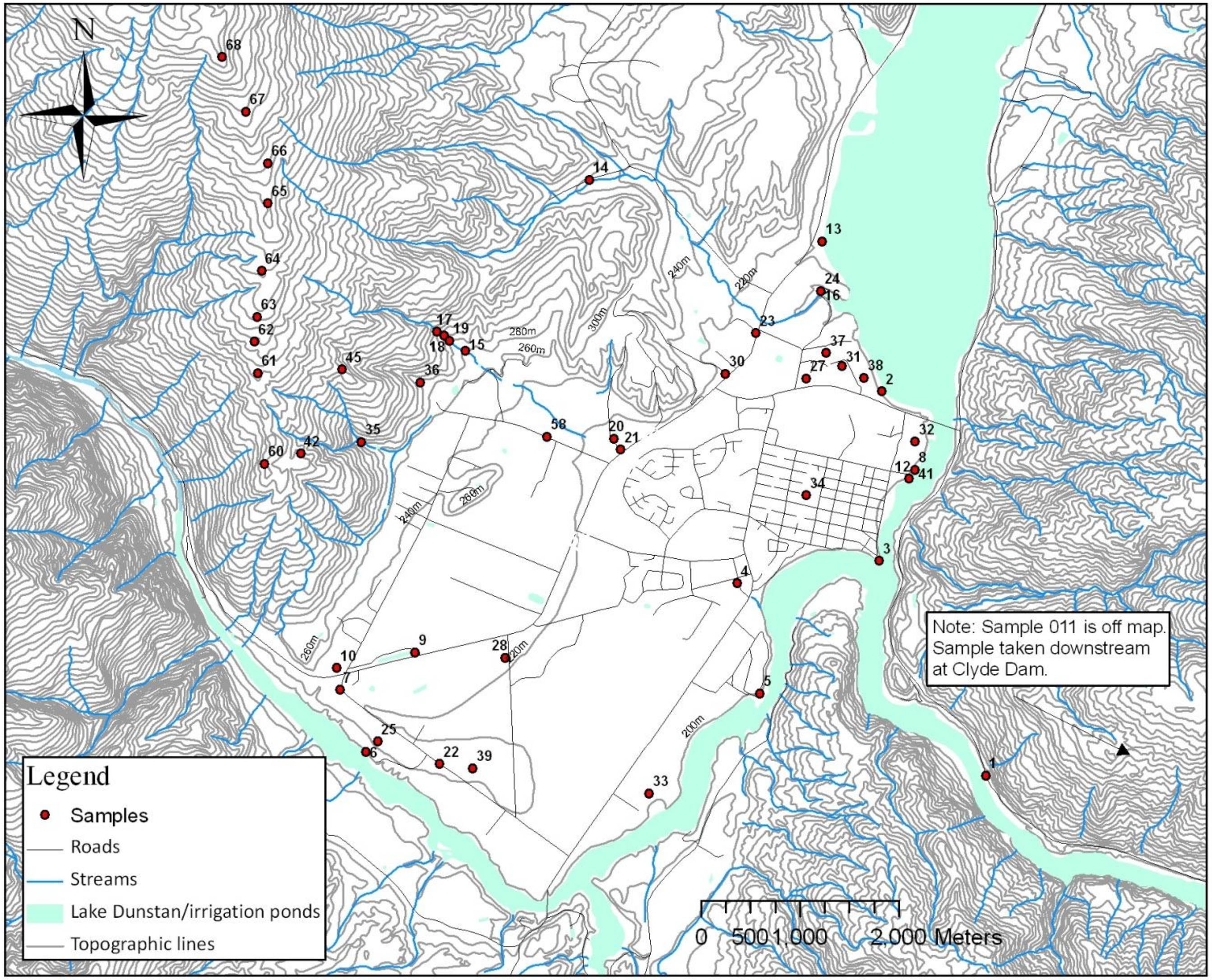
High elevation areas and colder temperatures cause ^{18}O to fractionate out from ^{16}O causing depleted ^{18}O ratios (Sharp, 2007). A large water body that undergoes evaporation will become enriched in ^{18}O. Since Lake Dunstan is a large water body it is expected that it will undergo evaporation and should be more enriched in ^{18}O than groundwater or precipitation on the Pisa Range.

Water samples from Lake Dunstan, Pisa Range streams, Pisa Range snowfall, water races, rainfall and groundwater were taken for stable isotopic analysis of oxygen and hydrogen. All samples were collected over 3 trips to Cromwell during April, May, and August 2010. A total of 50 samples were taken from 10 Lake, 7 stream, 9 snowfall, 3 rainfall, 4 water race and 17 bore localities. It should be noted that water in the water race is sourced from the Kawarau Arm as part of the Ripponvale Irrigation Scheme. Sample sites were selected on location, accessibility and source of the water being sampled (i.e. lake water, groundwater, stream, e.t.c.). Snow samples were collected approximately every 50 vertical metres from the snow line up to Mt Michael on the Pisa Range. Sample locations are shown in Figure 4.15.

Samples were collected according to the Institute of Geological and Nuclear Sciences National Protocol for State of the Environment Groundwater Sampling in New Zealand (2006). All samples were collected in 8ml plastic vials and kept chilled until laboratory analysis could be carried out. Surface water samples were taken by submerging the sample vial in the body of water until the vial was full. Bore water samples were taken as close as possible to bore head, and each bore was flushed before samples were taken to reduce the risk of surface water contamination in the bore. A minimum of three well volumes were purged by pumping as described in the Institute of Geological and Nuclear Sciences National Protocol for State of the Environment Groundwater Sampling in New Zealand (2006). For bores that had no pump, a disposable bailer was used to purge well before samples were taken.

All stable isotopic analysis of oxygen and hydrogen were carried out at the University of Canterbury's Stable Isotopic laboratory by Travis Horton in November 2010.

Figure 4.15 – Map showing locations where water samples were collected for stable isotopic analysis



The results are recorded in the typical δ notation format relative to V – SMOW for oxygen and hydrogen isotopic analyses (Stewart & Morgenstern, 2001).

$$\delta = \frac{\frac{R}{(R\ VSMOW) - 1}}{1000}$$

[R = $^{18}O/^{16}O$ or $^2H/H$ ratios of the sample and standard (VSMOW). Units are in parts per thousand (‰)]

Standard measurement errors for $\delta\ ^{18}O$ and $\delta\ ^{2}H$ are +/- 0.10‰ and +/- 1.0‰ respectively, (Stewart & Morgenstern, 2001). Appendix 4.8 shows the data for samples collected.

4.8.2 Results

Figure 4.15 shows a plot of the all the stable isotope data collected during this study with $\delta^{18}O$ and δ^2H values plotted against each other. Using the meteoric water samples, a Local Meteoric Water Line (LMWL) for the Cromwell area was found (Sharp, 2007). The Cromwell LMWL is the general linear trend of the local meteoric precipitation. The equation and R^2 of the Cromwell LMWL are:

$$\delta^2H = 7.3 \times \delta^{18}O + 1.7$$

$$(R^2 = 0.941)$$

The LMWL can be compared with the Global Meteoric Water Line (GMWL) which is the general linear trend of all global meteoric waters (Sharp, 2007).

The LMWL for Cromwell is not as steep as the GMWL and cuts across it (figure 4.16). Figure 4.16 also shows the LMWL lines for the Wakatipu and Wanaka Basins (Rosen et al., 1997). These two basins drain water that flows into Lake Dunstan. Both of these two Meteoric Water Lines (MWL) have similar slopes to the Cromwell LMWL with the Wakatipu Meteoric Water Line being almost identical. The Wanaka MWL lies above both the Cromwell LMWL and the Wakatipu MWL but all three cross the GMWL. These differences and/or similarities can be described by the deuterium excess parameter which is given by:

$$d = \delta^2H - 8\delta^{18}O$$

where *d* is the deuterium excess parameter (Sharp, 2007).

The present GMWL has deuterium excess parameter of +10‰. The deuterium excess parameters for the Cromwell LMWL and the Wakatipu MWL were +6.7‰ and +6.9‰ respectively, whereas the Wanaka MWL had a deuterium excess value of +9.4‰.

Figure 4.16 – Plot of oxygen 18 and deuterium for samples collected from Cromwell Flat, Lake Dunstan, Lake Wanaka and Lake Wakatipu. Local Meteoric Waters Lines for Cromwell (LMWL), Wakatipu basin and the Wanaka basin are shown along with the GMWL.

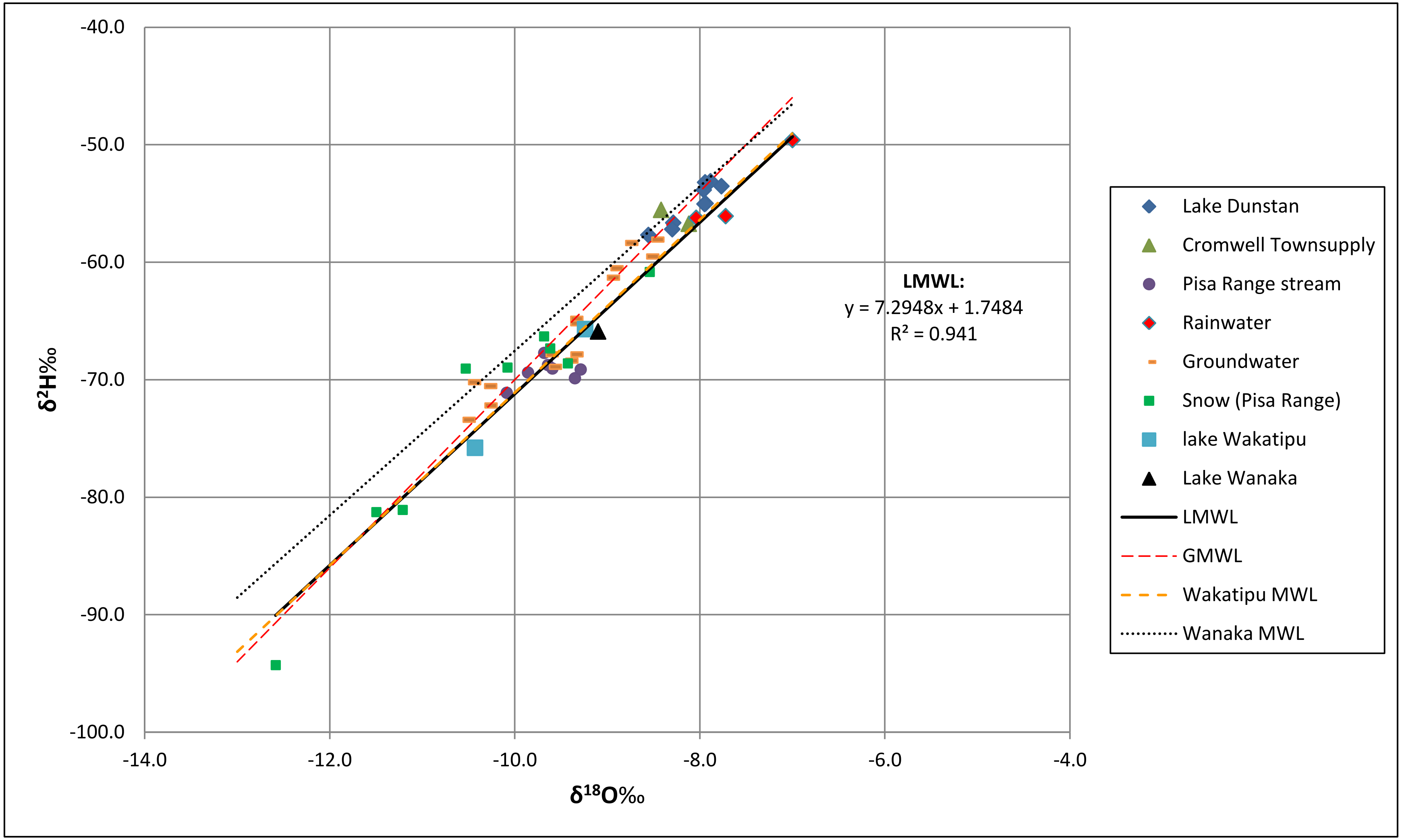


Figure 4.16 also shows the differences in the isotopic composition of waters from different areas in the Cromwell area. The average $\delta^{18}O$ and $\delta\,^{2}H$ values are shown in table 4.7. The Lake Dunstan samples and the rain water samples cluster together and are more isotopically enriched than most of the other samples. Samples from Lake Dunstan have an average $\delta\,^{18}O$ value of -8.1‰ whereas the rainwater samples have an average $\delta\,^{18}O$ value of -7.6‰. The Pisa Range stream samples also cluster together tightly and are more depleted than the Lake Dunstan samples with an average $\delta\,^{18}O$ value of -9.6‰. The groundwater samples are more spread out and are all generally more depleted in ^{18}O than the Lake Dunstan samples. The groundwater samples tend to form two clusters, one around the Pisa Range stream samples and the other just below the Lake Dunstan samples. Collectively the groundwater samples have an average $\delta\,^{18}O$ value of -9.5‰. Snow samples from the Pisa Range have a large spread with the most enriched sample having $\delta\,^{18}O$ value of -8.5‰, with the most depleted being -12.6‰. Collectively they have an average $\delta^{18}O$ value of -10.4‰ which is the lowest average value for all of the samples.

	$\delta^{18}O$ (‰)	**$\delta^{2}H$ (‰)**
Lake Dunstan	-8.1	-54.8
Irrigation water	-7.6	-54.2
Pisa Range stream	-9.6	-69.3
Pisa Range snow	-10.4	-73.1
Rainfall	-7.6	-54.0
Cromwell Town Supply	-8.3	-56.1
Groundwater	-9.5	-65.8
Combined average of Pisa Range snow, Pisa Range stream and rainfall	-9.2 +/- 1.4	-65.5 +/- 10.2

Table 4.7 – Table of the average oxygen 18 and deuterium values for samples from the Cromwell area. Uncertainties for the combined average of the Pisa Range snow, Pisa Range stream and rainfall values are one standard deviation.

When the surface of a snow pack is melted, the original isotopic composition of the surface snow changes due to isotopic enrichment from evaporation of the lighter isotopes. The melted surface snow then percolates downward through the snowpack into the deeper layers and refreezes, altering the isotopic composition of the deeper layers (Gat, 2010). Sampling of snow on the Pisa Range was carried out 2 days after the previous snowfall and may have experienced some melting, resulting in the large spread of values.

The isotopic signature of groundwater is typically the average of its recharge sources (Sharp, 2007). The combined average of Pisa Range snow, Pisa Range streams and rainfall samples give a $\delta^{18}O$ value of -9.2‰ +/- 1.4‰. This is similar to the average $\delta^{18}O$ value for groundwater (-9.5‰) and indicates that groundwater is recharged via a combination of Pisa Range snow melt, Pisa Range streams and rainfall on the Cromwell Flat.

The two Cromwell Town Supply samples had an average $\delta^{18}O$ value of -8.3‰, which is very similar to the average $\delta^{18}O$ value for Lake Dunstan (-8.1‰). Water for the Cromwell Town Supply is sourced via a groundwater bore located right on the edge of Lake Dunstan. The similarities in the isotopic signatures suggest that the Cromwell Town Supply bore is drawing water derived from Lake Dunstan. However, the average $\delta^{18}O$ value of -8.3‰ for the Cromwell Town Supply is slightly more depleted than water from Lake Dunstan. This could indicate some mixing with groundwater at the lake margin.

Contour maps were created using the ^{18}O and ^{2}H data from groundwater, lake water, Pisa Range stream and Cromwell Town supply samples that were collected during this study. These maps are displayed in figures 4.17 and 4.18. Rosen et al (1997) used similar groundwater isotopic contour maps to show the distribution and flow direction of groundwater for the Wanaka and Wakatipu basins.

Both figures show plumes of isotopically depleted water moving outward from the interior of the Cromwell Flat away from the Pisa Range and its streams toward the lake in a manner similar to the water level contour maps. The ^{18}O and ^{2}H maps show that recharge to the CTA is sourced from the Pisa Range, with groundwater flow moving outward toward Lake Dunstan. The contours steepen closer to the lake margin, indicating the transition from groundwater to lake water. This transition is very abrupt where the contours are steeper or closer together. Where the contours aren't as close together, the transition is more gradual, indicating some infiltration of lake water into the margins of the CTA, creating a 'mixing - fringe ', around the edge of the aquifer where lake water and groundwater mix. Samples from the Cromwell Town Supply bore on the edge of Lake Dunstan support this idea of a mixing – fringe in the aquifer at the lake margin. Both maps show very steep contours at McNulty inlet, suggesting that there is very little infiltration of lake water into the aquifer at this point.

There are two anomalies in the data that form 'bulls eyes' in the interior of the Flat which show the groundwater to be more enriched. The presence of these maybe from contamination of rainwater in the bores during sampling, although both bores were purged before sampling. There is also a lack of

Figure 4.17 – Oxygen 18 contour map of CTA, Pisa Range streams and Lake Dunstan.

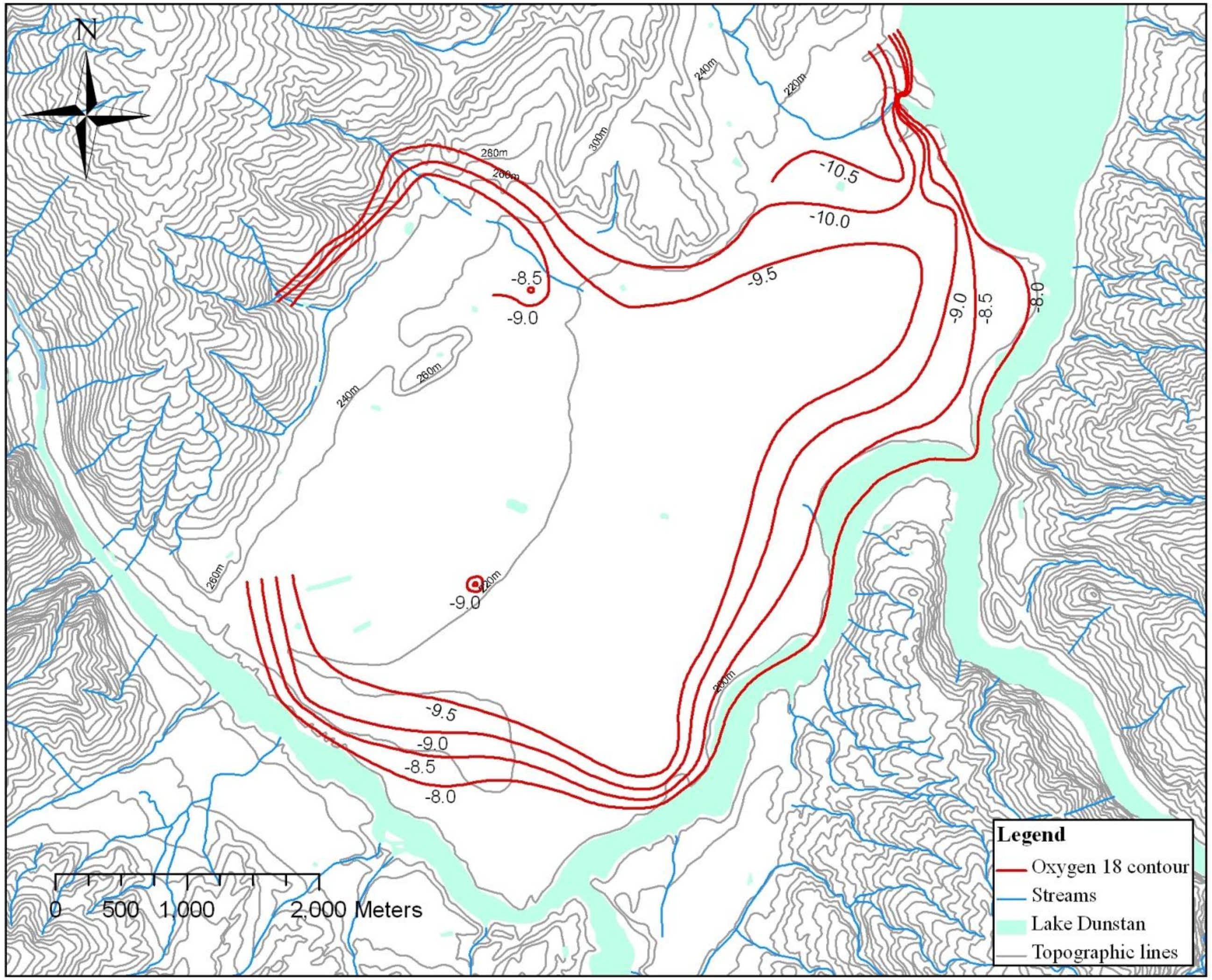
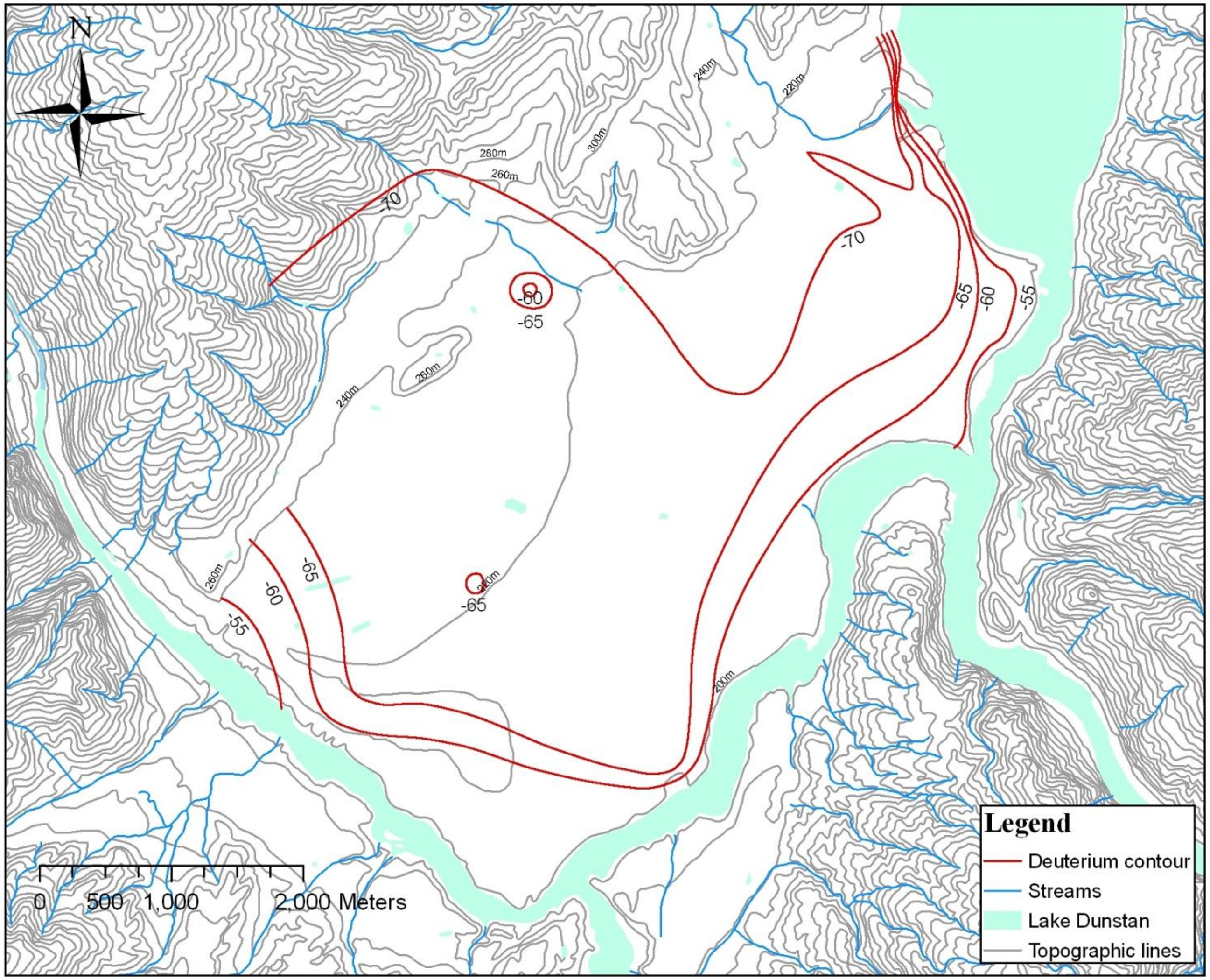


Figure 4.18 – Deuterium contour map of the CTA, Pisa Range streams and Lake Dunstan.



data surrounding these two bores and the rest of the interior of the Cromwell Flat. With more data, these two enriched groundwater samples could be explained.

4.10 Discussion

The water chemistry of all samples was dominated by the cation – anion pair of calcium and bicarbonate. In a similar study carried out in the Wanaka and Wakatipu basins, Rosen et al. (1997) found that calcium and bicarbonate were the dominant cation – anion pair as well. The source of the calcium and bicarbonate was determined to be dissolved calcite, which is an accessory mineral in the Otago Schist (Coombs et al., 1985). The dominant control on the water chemistry in Central Otago is the Otago Schist.

Analysis of the water chemistry data showed that groundwater samples closer to the Pisa Range had higher ionic concentrations than groundwater samples nearer the lake margin. Lake samples had the lowest ionic concentrations. Rosen et al (1997) found a similar occurrence in the Wanaka basin with groundwater samples closer to large schist outcrops and mountain ranges having higher calcium and bicarbonate concentrations than samples further away from schist outcrops. Rosen et al. (1997) suggested that snow melt and precipitation on the mountain ranges percolated down through the schist, dissolving ions along its path through fractures in the bedrock, before flowing out into the groundwater system in the Wanaka basin. Mixing with meteoric precipitation and surface flows later reduced the concentrations of calcium and bicarbonate. From this, it can be suggested that groundwater in CTA flows out from fractures in the schist of the Pisa Range. The concentrations of ions are gradually reduced as the groundwater flows toward the lake Dunstan and mixes with the lake water in the fringes of the aquifer and infiltration of rainfall on the Cromwell Flat. The reduction in the ionic concentration is more likely to be from mixing with lake water than meteoric precipitation on the Cromwell Flat surface as the annual precipitation is very low and the amount of evaporation is far greater than precipitation. However large rainstorms on the Cromwell Flat may provide enough water to infiltrate into the aquifer to reduce the ionic concentration.

Close and McCallion (1988) suggested that excessive irrigation may result in salts from the saline patches in some soils on the Cromwell Flat to cause leaching of salts into the groundwater system. The SAR (sodium absorption ratio) showed that so far there has been little leaching of sodium into the aquifer. This may be due to the areas where these saline patches exist not being irrigated.

Isotopic analysis showed that the groundwater of the CTA is more depleted than Lake Dunstan and rainfall. This is most likely due to Lake Dunstan experiencing evaporation and mixing with rainwater which would enrich the lake water in $\delta^{18}O$ relative to groundwater. The combined average of Pisa

Range stream, Pisa Range snow and rainfall gave a $\delta^{18}O$ value very similar to the average ^{18}O value for groundwater. This indicates that groundwater is recharged via a combination of Pisa Range snow melt, Pisa Range stream flow and rainfall on the Cromwell Flat. The Cromwell LMWL had deuterium excess parameter (+6.7‰) almost identical to the deuterium excess parameter of the Wakatipu MWL (+6.9‰). The Wanaka MWL had a similar slope but had a higher deuterium excess parameter (+9.4‰). The similarity between the Cromwell LMWL and the Wakatipu MWL may suggest that meteoric precipitation is supplied from the same weather systems. Since all samples were collected during the autumn and winter periods, the Cromwell LMWL may reflect the air masses of this time of the year (Lee et al., 1999).

Ideally, all water samples for hydrochemical analysis needed to have been collected during the same hydrological year. Water samples from the Pisa Range streams should have been included in the hydrochemical analysis, as the isotopic analysis shows that they have a similar isotopic composition to the groundwater of the CTA. More groundwater samples from the interior of the Cromwell Flat are needed as there is a lack of data in this area. Isotopic sampling of all waters should be carried out during both winter and summer to determine if there is a seasonal variation.

4.11 Chapter Summary

Water chemistry from selected bores and Lake Dunstan and its tributaries showed that no samples transgressed the Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008) for nitrate – nitrogen and all but one for pH. The lower pH of this sample was interpreted to be from possible contamination, due to the consistency of the pH values for the rest of the samples, and its close location to other nearby samples with acceptable pH values.

Pie diagrams of cation and anion concentrations show that concentrations are higher in the interior of the Cromwell Flat and lower toward the lake margin. Ionic concentrations for Lake Dunstan and its tributaries are all significantly lower than that of the groundwater samples.

Piper diagrams showed all waters analysed can be classified as calcium – bicarbonate waters. The source of the calcium and bicarbonate is from dissolved calcite, a secondary mineral in the basement Otago Schist.

The Stiff Patterns showed that groundwater could be divided into 3 different groups depending on their shape. Samples from Lake Dunstan and its tributaries could be divided into 2 groups based on their shape.

Stable isotopic analysis showed that CTA groundwater is more depleted than water from Lake Dunstan and meteoric precipitation. The average $\delta^{18}O$ value for groundwater was -9.5‰ whereas the average $\delta^{18}O$ value for samples from Lake Dunstan was -8.1‰. The combined average of Pisa Range streams, Pisa Range snow and rainfall $\delta^{18}O$ values gave a $\delta^{18}O$ value of -9.2‰ +/- 1.4‰ which is very similar to the average ^{18}O value for groundwater. This indicates that recharge to the CTA is a combination of Pisa Range snow melt, Pisa Range streams and rainfall on the Cromwell Flat.

Contour maps of both the ^{18}O and ^{2}H show that there is a 'mixing fringe' around the edge the CTA where groundwater mixes with lake water that has infiltrated into the aquifer.

Chapter Five

Conceptual Recharge Model of the CTA and Groundwater Allocation

5.1 Introduction

In a groundwater system it is important to understand where recharge is sourced (inflows) and where the outputs (outflows) of the system are. Once these are known, groundwater can be traced from its source to where it exits the groundwater system. An understanding of the path groundwater takes through a groundwater system is fundamental for calculating a water balance and allocating groundwater.

Chapter 5 discusses the sources of recharge and outflow of the CTA and attempts to combine these into a conceptual recharge model where groundwater can be traced from its source through the groundwater system. Once all the inputs and outputs of the aquifer are identified from the recharge model, a water balance can be created to estimate the volume of water that passes through the aquifer. From the water balance an allocation scheme can found that will allow sustainable abstraction of groundwater without over extraction of the resource.

5.2 Conceptual Recharge Model

From Chapters 3 and 4, the sources of recharge to the CTA were identified. Chapter 3 identified that groundwater flows away from the Pisa Range toward Lake Dunstan and the Kawarau Arm. Fluctuations in groundwater levels suggest seasonal recharge.

The calcium bicarbonate dominated chemical composition of the CTA indicates that groundwater passes through the Otago Schist of the Pisa Range. Calcite in the Otago Schist is dissolved into solution as the groundwater flows down through fractures and joints in the Schist before flowing out into the aquifer. Rosen et al. (1997) suggested that the water coming out of the Schist into the Wanaka Basin was snowmelt from higher elevations that had filtered down through the Schist before flowing out into the local groundwater system. From the water chemistry data, it appears there is a similar recharge process occurring in the CTA.

The reduction in calcium bicarbonate concentrations as groundwater moves outward toward Lake Dunstan suggests mixing with Lake Dunstan and the infiltration of precipitation into the aquifer on Cromwell Flat. Both Lake Dunstan and rainfall have low concentrations of calcium – bicarbonate concentrations and mixing with groundwater with high concentrations would result in them being reduced.

Stable isotopic analysis of water from different sources around the Cromwell Flat suggested that groundwater is recharged from a mixture of Pisa Range snow melt, Pisa Range streams and rainfall. Contour maps of ^{18}O and ^{2}H data for the Cromwell Flat showed that there is mixing fringe at the lake margin of the CTA, indicating that lake water infiltrates a short distance into aquifer and mixes with groundwater.

Using this information, a conceptual recharge model can be generated.

- Snowmelt on the Pisa Range filters down into the Otago Schist through fractures and joints where it dissolves calcite into solution. From here the water flows down through the schist and enters the CTA in the subsurface.
- Surface water on the Pisa Range is funneled down the active streams off the Pisa Range were it enters the aquifer at the base of the Pisa Range by infiltrating down through the Cromwell Flat surface.
- Rainfall on the Cromwell Flat infiltrates down into the CTA.
- Groundwater flows outward from the Pisa Range toward Lake Dunstan.
- At the lake margin, groundwater mixes with lake water that has infiltrated into aquifer before flowing out into Lake Dunstan

Figure 5.1 provides a graphical interpretation of the recharge model for the CTA.

It is unknown how much groundwater flows out of the Schist of the Pisa Range and recharges the CTA. How much of an impact the Pisa Fault zone has on subsurface recharge from the schist is also not known. The Pisa fault zone is made up of highly sheared and fractured schist with seams of clay infilling some of the shears. These clays seams in the fault zone may impede groundwater flow or, alternatively, the highly sheared and fractured nature of the schist in this zone could provide conduits for water flow.

This recharge and outflow model for the CTA can be used to help allocate the groundwater resources for the Cromwell Flat so that groundwater can be used sustainably.

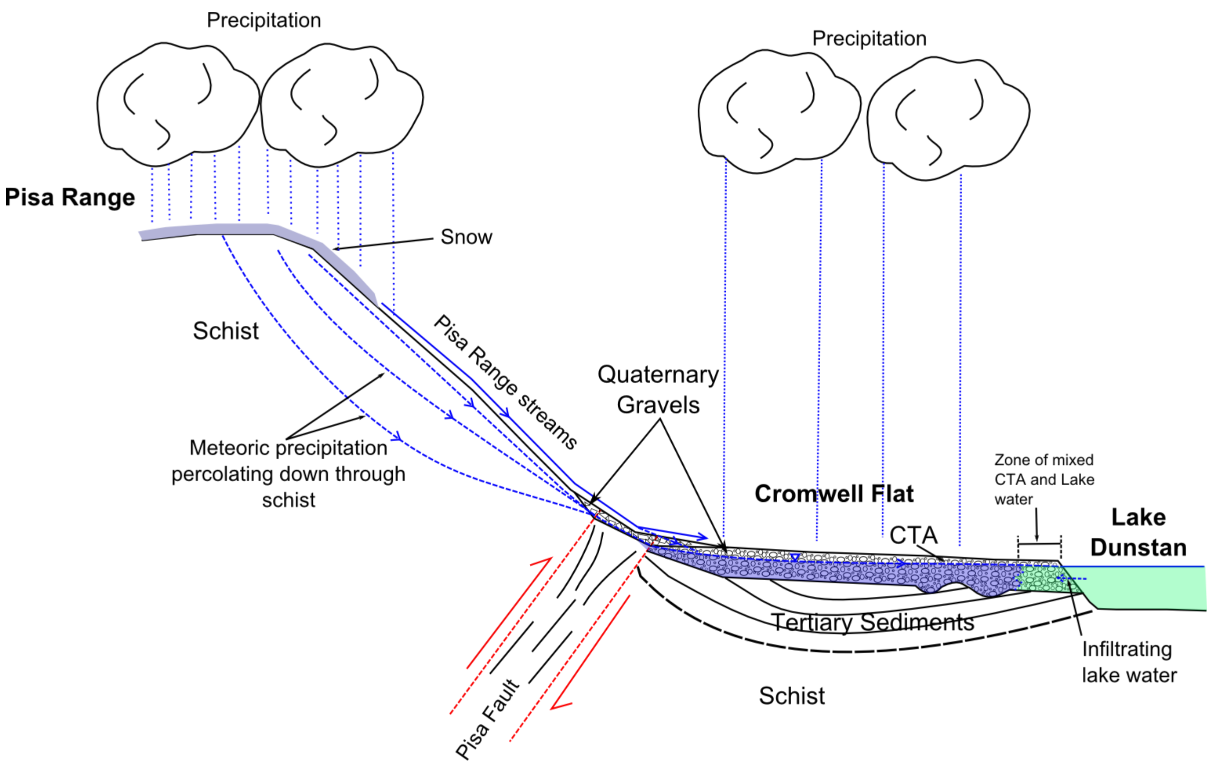


Figure 5.1 – Schematic of the conceptual recharge model for the CTA. Diagram shows recharge to aquifer, outflow into Lake Dunstan and the partial infiltration of Lake Dunstan into the CTA. (not to scale)

5.3 Water Balance

Allocation of groundwater is an important part of maintaining a sustainable groundwater resource. It provides a quantified volume of water that can be sustainably extracted without causing a reduction in water quality and the depletion of groundwater resource (Zhou, 2009). One of the most common methods used in the process of allocating groundwater resources is using a water balance to analyze the physical inputs and outputs of a groundwater system by looking at the magnitudes of these parameters. The water balance takes into account the spatial extent of a groundwater system and how it varies with time (Serban & Askew, 1991). From this, groundwater allocation volumes can be estimated so that sustainable yield of the water resource occurs. In this section a water balance for the CTA is developed.

During the course of this study, the O.R.C. carried out a water budget for the CTA as part of a region wide evaluation of the major groundwater basins of Otago (Wilson & Lu, 2011). This water balance concentrated on recharge to the aquifer from solely infiltration of precipitation through the soils of the Cromwell Flat itself through and used the Ruston et al. soil moisture balance method of estimating recharge.

The water balance for this study uses a simpler approach than the O.R.C. water balance (Wilson & Lu, 2011) but utilising the information gathered from the conceptual recharge model of the CTA provided in section 5.1, this water balance takes into account outflows from the CTA into Lake Dunstan and all inflows into the aquifer from the Pisa Range (Stream flow, snowmelt and subsurface flow) and rainfall on the Cromwell Flat.

5.3.1 Water Balance Methodology

A water balance is based on the law of mass conservation where mass is transferred throughout a system (Vorster, 1985). In hydrogeology this is known as the hydrologic equation and for a particular system over a specific amount of time it is given in its simplest form as:

Inflow +/- Change in Storage = Outflow

Inflows are all inputs to the system such as natural and artificial recharge to an aquifer where as outflows are all natural and artificial removal of water from the system over a specified time period

Inflows	**Description**
Precipitation	Rainfall e.t.c. across the entire field area (Cromwell Flat and the Pisa Range catchment)
Surface flows	Pisa Range streams that drain the catchment on the Pisa Range
SWE (Snow water equivalent)	The volume of water equivalent from snowmelt on the Pisa Range catchment
Irrigation	Artificial recharge from irrigation from water extracted from the Kawarau arm as part of the Ripponvale water scheme as of 2009
Inflow from the Pisa Range	Inflow of water from fractures in the bedrock schist of the Pisa Range
Outflows	
Evaporation	Evaporation of surface water across the entire field area (Cromwell Flat and the Pisa Range catchment)
Groundwater extraction	Artificial extraction of groundwater via bores and pumps from the CTA as of 2010
Evapotranspiration	Transpiration of plants across the entire field area (Cromwell Flat and the Pisa Range catchment)
Outflow into Lake Dunstan	Groundwater flow out of the aquifer into Lake Dunstan
Change in Storage	The change in storage for the CTA is the seasonal fluctuations in the CTA per year.

Table 5.1 - Table listing the parameters used in the calculation of the water balance for the CTA.

(Freeze & Cherry, 1979). Change in storage is the change in the volume of the system for a specified time period. All units are given in volume per unit time or cubic metres per yr (m^3/yr).

Vorster (1985) describes the process of creating a water budget involving 3 factors; free body, time interval and base period. The free body is the defined area for which the water budget is derived. For the CTA described in this study, the free body is Cromwell Flat and its catchment on the Pisa Range and Foothills. The time interval is the period of time for which the water budget is carried out for. For this study the time period is for one year. Base period is the time interval in the historic data in which data is collected in (Vorster, 1985). For this water budget the precipitation, evaporation, and evapotranspiration data for Cromwell used in this study was collected over a 30 year period from 1970 to 2000 (NIWA, 2010). The data from this base station was used as it was collected over the longest period of time, and included data from years close to when this study was carried out.

A list of the inflows, outflows and the change in storage for the CTA are displayed in table 5.1

All of the parameters were quantified directly from physical measurements except the outflow of water into Lake Dunstan and inflow from the Pisa Range. These were quantified indirectly and residually from using hydrogeologic data and balancing the hydrologic equation.

Precipitation, evaporation and evapotranspiration data were collected from the NIWA Cliflo online database (NIWA, 2010). Groundwater extraction volumes and irrigation measurements were all sourced from the O.R.C. database and the Ripponvale water scheme (Murphy & O.R.C., 2009; O.R.C., 2010a). SWE and surface flows were measured during the course of this study. While the surface flows off the Pisa Range are entirely diverted away from their stream beds, it is assumed that this water is solely used for irrigation, recharging the aquifer. Outflow into Lake Dunstan was estimated by finding the flow rate of the CTA for one year. Inflow from Pisa Range bedrock was estimated as a residual by completing the hydrologic equation. Change in storage of the CTA is the annual fluctuation within the aquifer. Since these fluctuations are even and consistent, the change in storage is considered to be negligible.

All calculations and data used for quantifying these parameters are described in appendix 5.3. The Pisa Range catchment and foothills is shown in figure 3.1.

5.3.2 Water Balance Results

A summary of the results of the water balance for the CTA are displayed in table 5.2.

The dominant inflows are from precipitation and inflows from the Pisa Range Bedrock. The dominant outflows are evaporation and outflows into Lake Dunstan. Current groundwater extraction and

Annual Water balance for Cromwell Terrace Aquifer			
Inflow (M m^3/yr)		**Outflow (M m^3/yr)**	
Precipitation	20	Evaporation	64
Surface flows	0.03	Groundwater extraction	3
SWE	0.2	Evapotranspiration	0.2
Irrigation (Kawarau)	3	Outflow into Lake Dunstan	25
Inflow from Pisa Range bedrock	70		
Total Inflow (M m^3/yr)	93	**Total outflow (M m^3/yr)**	93

Table 5.2 – Summarized water balance for the CTA.

irrigation from the Ripponvale water scheme are both very insignificant compared to the dominant inflows and outflows.

5.3.3 Water Balance Discussion

The basic water balance described above, relies on a number of assumptions. These assumptions are:

- There is no inflow from Lake Dunstan in the Kawarau Arm
- The aquifer is of equal thickness and is heterogeneous in every direction
- No seepage down into the Tertiary sediments beneath the CTA
- Doesn't take into account soil moisture
- All irrigation water from the Ripponvale water scheme percolates down into the aquifer and is applied all year around
- All bores included in this study that do not have resource consent extract groundwater at the maximum rate of 25 m^3/yr
- All groundwater extracted artificially doesn't end up back in the aquifer
- Snowmelt is available all year round

Some of these assumptions were put in place for ease of calculating the water balance, where as others arose due to it being extremely difficult to quantify their parameters. These assumptions will create some errors in the water balance.

The total volume of water that passes through the CTA system per year as calculated from the water balance is 93 Mm^3yr. The dominant factors of the CTA system in terms of its water balance are the inflow of water from the Pisa Range bedrock and large volume of evaporation. Since evaporation (64 Mm^3/yr) is much greater than the combined surface inflows (precipitation, surface flows, SWE and irrigation = 23 Mm^3yr), the CTA system operates at a net deficit, reflecting the semi arid nature of the area. This is balanced out by the inflow from Pisa Range bedrock (70 Mm^3yr).

Unfortunately inflow from the Pisa Range bedrock could only be calculated as a residual as it would be extremely difficult to physically measure this inflow. Whether or not the Pisa Fault zone or the folded Tertiary sediments would restrict subsurface inflow is unknown. Further research into the water chemistry of the Pisa Range streams and stable isotopic analysis of water samples from within the subsurface of the Pisa Range would help to improve understanding of this.

Compared to the water balance carried out by the O.R.C., the total volume of water passing through the CTA as calculated from this study is significantly greater. The O.R.C. water budget calculated that there is only 1.2 Mm^3yr passing through the system as opposed to 93 Mm^3yr. This significant difference is due to the fact that this water balance takes into account recharge and evaporation on the Pisa Range. The O.R.C. water balance concentrates solely on recharge from precipitation on Cromwell Flat itself. It is interesting to note that the current volume of water being extracted from the CTA at the time of this study (3.4 Mm^3yr) is greater than the volume of water the O.R.C. water balance calculated (1.2 Mm^3yr) to be passing through the CTA system.

5.4 Groundwater Allocation

Groundwater allocation is typically employed to make sure a groundwater resource isn't over extracted. Historically the volume of water that could be 'safely' extracted was thought to be no more than the natural recharge. Over time this has been disproved, and the generally excepted volume of water that can be 'sustainably' extracted is now a volume much less than the natural recharge (Aitchison-Earl et al, 2004; Zhou, 2009).

At present the CTA has no groundwater allocation measures in place for the CTA. Landowners can extract up to 25 m^3/day without resource consent or informing the O.R.C. Groundwater abstractions over 25 m^3/ yr require resource consent and the O.R.C. keeps a record of how much is extracted from each bore (O.R.C., 2011). There are a number of different methods of water groundwater allocation that generally depend on the geography and climate of the area under question. In Otago, the O.R.C. typically use one or a combination of three different methods for determining groundwater allocation.

These are:

1. 50% of mean annual rainfall
2. Combined allocation with connected surface water flows/bodies

3. Volume specified after scientific investigation and community consultation from Plan Schedule 4A of the O.R.C. Water Plan for Otago (O.R.C., 2011b)

(Jens Rekker, pers comm, 2010)

In similar groundwater studies in the Alexandra basin and Ettrick basin, methods 1 and 2 were employed with groundwater and surface flows considered to be a single resource and an allocation of 50% of the annual mean natural recharge (Bekesi, 2005; O.R.C., 2006). Aquifers in the Alexandra Basin are very similar to CTA as they are made up of unconsolidated Quaternary gravels on top of less permeable Tertiary sediments and the area has a similar climate.

The CTA is complicated by Lake Dunstan which has greatly increased the storage of the aquifer and the fact that Lake Dunstan can infiltrate into the aquifer. Bores near the lake margin may extract lake water as opposed to groundwater supplied via recharge from the Pisa Range. An allocation scheme using the 70 Mm^3yr inflow from the Pisa Range bedrock could be created as it the dominant inflow to the CTA. However, since this volume was calculated as a residual, it will be susceptible to calculation errors and it may not be wise to use this value for allocating groundwater.

The default option for groundwater allocation for the CTA would be to allocate 50% of mean annual rainfall to the aquifer for abstraction. The 20 Mm^3/yr volume was calculated using data that was physically recorded, as opposed to being residually calculated. Since the mean annual precipitation to the CTA is 20 Mm^3/yr, the allocated volume for abstraction would be approximately 10 Mm^3/yr. This is much greater than the present volume of abstracted groundwater estimated by this study. Using this allocated volume, there is still another 7 Mm^3/yr of groundwater which can be sustainably abstracted. Due to the small size of the Cromwell Flat, types of land use, availability of surface water from Lake Dunstan and the volume of groundwater users, it is unlikely that this volume of water would ever be fully allocated. Even though precipitation is much smaller than evaporation, any deficits are likely to be buffered by lake water infiltrating into the aquifer.

If more than 10 Mm^3/yr of water was extracted from the aquifer, it is likely that there would be little draw down of the level of the CTA due to Lake Dunstan infiltrating into the aquifer and filling in any cones of depressions. Even during dry years when recharge is reduced, Lake Dunstan will act as a buffer by maintaining the aquifer at a constant height. More information is needed to fully understand the interactions between Lake Dunstan and the CTA. Due to the small land area, types of land use, population density of Cromwell Flat and availability of surface water (i.e. Lake Dunstan), it is unlikely that the total volume of 10 Mm^3/yr will be fully allocated.

Using the method of allocating 50% of the mean annual precipitation volume may be a better option in place of allocating a volume using the inflow from the Pisa Range bedrock as there are less errors involved in the calculation of the mean annual precipitation volume. The mean annual precipitation volume (20 Mm^3/yr) was calculated using data that was physically recorded, where the inflow from the Pisa Range bedrock volume (70 Mm^3/yr) was residually calculated.

5.5 Chapter Summary

A conceptual model of recharge to the CTA was created using information gathered in the previous chapters of this study. The model showed that recharge to the CTA is a combination of meteoric precipitation on the Pisa Range filtering down through the schist of the Pisa Range, surface flows down Pisa Range streams and precipitation on the Cromwell Flat itself. Groundwater in the CTA then flows outward into Lake Dunstan. A 'mixing - fringe' where groundwater and lake water mix was found to exist at the edge of the aquifer.

The water balance for the CTA used the simple hydrologic equation to evaluate the inflows and outflows of the CTA. The water balance found that the dominant inflow was from water flowing into the aquifer from the Pisa Range schist, while the dominant outflow was evaporation. The total volume of water that passes through the CTA is 93 M m^3/yr.

A volume of groundwater was allocated using the method of restricting the total volume of groundwater available for abstraction to 50% of the natural precipitation that recharges the aquifer. The natural precipitation that recharges the aquifer was 20 M m^3/yr. Using the 50% rule, there is 10 M m^3/yr of groundwater that can be sustainably abstracted from the CTA

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Chapter Six

Summary and Recommendations

6.1 Project Aims

The overall aim of this study was to obtain a better understanding of the inflows and outflows of the Cromwell Terrace Aquifer (CTA), and to evaluate aquifer interactions with Lake Dunstan. From this a water balance was calculated so a sustainable allocation scheme for the CTA could be created. A combination of water contour maps, stable isotopic analysis, water chemistry and a hydrogeologic model were used to achieve this.

6.2 Geology and Geomorphology

The CTA is made up of a thin veneer of Quaternary glacial outwash gravels that typically range in thickness from 10 to 30m, although in the paleochannels at the southern end of the Cromwell Flat the thickness of the gravels can range up to 50m. These gravels rest on top of an eroded and scoured surface in the less permeable Tertiary sediments beneath. The Tertiary sediments are all confined to the Cromwell – Tarras basin, which is a synform structure in the folded Otago Schist basement. These sediments are made up almost entirely of lacustrine sediments which have a low permeability. The Tertiary sediments form the hydrological basement of the CTA.

The Quaternary outwash gravels of the CTA are sourced from glaciations further up the Cromwell – Tarras Basin, and also from the Wakatipu Basin, during the late Quaternary. These gravels were deposited in a braided river fluvial environment at the confluence of the Clutha and Kawarau Rivers. The Cromwell Flat is made up of two outwash gravel deposits. These are the Luggate gravels (140,000 – 70,000 years) and the Albert Town gravels (85,000 – 35,000 years), with the older gravels concentrated at the base of the Pisa Range and the younger gravels making up most of the Cromwell Flat surface and along the lake margin. The Luggate outwash gravels interfinger with contemporaneous alluvial fan gravels off the Pisa Range.

Both the Luggate and Albert Town outwash gravel have a similar lithologic description of "sub rounded to rounded, sandy gravel to cobbly sandy gravel with some silt and boulders" (Officers of the New Zealand Geological Survey, 1984; Turnbull, 2000). Due to the channelled nature of the environment in which the gravels were deposited; lenses of sands, silts and cross bedded gravels are common. These lenses may impede groundwater flow, but since they are relatively small (1 to 3 m wide and 0.5 to 1 m thick), any influence on groundwater is likely to be localised.

The hydrological basement of the CTA is the contact between the younger Quaternary gravels and the older Tertiary lake sediments beneath. This contact influences the flow of groundwater in the CTA by reducing or stopping groundwater flow entirely. The paleochannels at the southern end of the Cromwell Flat have been eroded into the Tertiary sediments, and prior to the filling of Lake Dunstan, were one of the few places where groundwater could be extracted. The filling of Lake Dunstan increased the height of the groundwater table by 11 m, and as a result, groundwater can now be extracted from areas of the Cromwell Flat where it previously couldn't.

The surface of the Cromwell Flat is made up of a number of small alluvial terraces and some channel remnants, although these are hard to identify now due to land development. The terrace risers are useful in identifying the spatial extents of the Luggate and Albert Town outwash gravels. The most obvious geomorphological feature is the Ripponvale Hill, which is an anomalous mesa of less permeable Tertiary sediments. This may have a localised affect on the flow of groundwater, by diverting flow around and away from it. The Pisa fault runs along the base of the Pisa Range at the Back of the Cromwell Flat, and may control groundwater flow out of the schist bedrock.

6.3 Groundwater Flow and Recharge

Groundwater cross-sections constructed from bore log descriptions and geophysical data were used to show that the CTA is a single unconfined aquifer. Depth to groundwater varies from 11 m at the lake margin to 35 m near the base of the Pisa Range. The saturated thickness of the aquifer ranges from 10 m near the lake – margin to 30 m in the paleochannels at the southern end of the Flat.

Hydraulic conductivity for the CTA was found to be in the range of 45 – 60 m/day with transmissivities of 750 – 800 m^2/day. These values indicate that the gravels of the CTA impede groundwater flow very little. The hydrological properties of the CTA are similar to other gravel aquifers in the Clutha River Valley of similar age. Unfortunately, due to a lack of sufficient pump test data, the hydrological properties of the CTA have been established from only one bore at the southern end of the Cromwell Flat. This bore is located in the Albert Town outwash gravels and there is no data on the hydrological properties of the Luggate outwash gravels.

Groundwater contour maps show that groundwater flows outward from the Pisa Range and Burns Cottage Road Gully toward Lake Dunstan in south easterly and south westerly directions, indicating recharge from the Pisa Range.

Data collected during and after the filling of Lake Dunstan of groundwater levels in bore F41/350 indicate that the aquifer is recharged via seasonal precipitation, with the minimum groundwater levels occurring during the late winter months and maximum groundwater levels occurring during the late summer months. The annual fluctuations in the groundwater level of the CTA were measured to be between 0.4 – 0.5 m, with a maximum elevation of 195.6 masl in March and a minimum elevation of 195.1 masl in September. At the lake margin, the level of the CTA is maintained at a constant elevation due to Lake Dunstan remaining at a relatively constant elevation year round as the operating range of Lake Dunstan is only 1 m. From this, it could be suggested that the CTA is not recharged by Lake Dunstan, but by meteoric precipitation, predominantly in the late summer months. However, since summer is the main irrigation season, the higher levels in the groundwater table during the summer months may be due to artificial recharge from irrigation and seepage from water in the Ripponvale Irrigation Scheme canals and storage ponds.

Surface flows in the Cromwell Flat area are restricted to 3 active streams, and a number of dry drainage streams that run off the Pisa Range. These 3 active streams have a very low combined flow rate, with a large portion of the water they carry being removed for irrigation. There are no natural streams that flow across the Cromwell Flat, but the Ripponvale Irrigation Scheme transports water extracted from the Kawarau River along canals and channels to users across the Cromwell Flat. Groundwater contour maps show that groundwater flows away from where the streams and drainages stop at the base of the Pisa Range. This would suggest that the CTA is recharged via the Pisa Range.

Seasonal fluctuations, along with groundwater flow away from the Pisa Range, indicate that the CTA is recharged via water sourced from the Pisa Range.

6.4 Groundwater Chemistry and Stable Isotopic Analysis

Water samples collected by the O.R.C. from June 1994 to September 2006 show that only one sample transgressed the Ministry of Health (2008) Drinking-water Standards for New Zealand 2005 (Revised 2008) for pH. This sample was interpreted to be contaminated, due to the consistency of the pH values for the rest of the samples, and its close location to other samples with acceptable pH values.

Ionic concentrations tend to decrease from the middle of the Cromwell Flat toward the lake margin, with sample from Lake Dunstan having very low Ionic concentrations compared with samples from the CTA. Piper diagrams and Stiff patterns showed that the water of the CTA could be divided into 3 groups, with calcium and bicarbonate being the two dominant chemical constituents of all waters sampled. The source of the calcium and bicarbonate is calcite, an accessory mineral in the Otago Schist. The high concentrations of calcium and bicarbonate in groundwater samples closer to the Pisa Range indicate that groundwater is recharged with water that has passed through the schist via fractures and joints in the subsurface of the Pisa Range.

Stable isotopic analysis using ^{18}O and ^{2}H showed that groundwater was more depleted than meteoric water or water from Lake Dunstan. The average $\delta^{18}O$ value for groundwater was -9.5‰ whereas samples from Lake Dunstan had an average $\delta^{18}O$ value of -8.3‰, confirming that Lake Dunstan is not a recharge source. Water samples from the Cromwell Town Supply gave an average $\delta^{18}O$ value of -8.3‰. The source of the Cromwell Town Supply is a groundwater bore right on the lake margin. The isotopic signature of samples from the Cromwell Town Supply would suggest it is a mixture of lake water and groundwater.

Pisa Range snow samples, Pisa Range streams and rainfall on the Cromwell Flat gave an average $\delta^{18}O$ value of -9.2‰ +/- 1.4‰, which is very similar to the average ^{18}O value for CTA groundwater. Groundwater typically has an average composition of its recharge sources, suggesting that snow melt and surface runoff from the Pisa Range, combined with rainfall on the Cromwell Flat, are the principal recharge sources for the CTA.

6.5 Water Balance and Allocation

Using the information gathered from this study a conceptual model of the recharge sources for the CTA was created. The model showed recharge is predominantly meteoric precipitation on the Pisa Range, combined with some precipitation on the Cromwell Flat. Precipitation on the Pisa Range is transported to the CTA via streams and shallow subsurface flows. Water then flows through the CTA outward into Lake Dunstan, where there is a buffer zone of lake water that has infiltrated and mixed with groundwater.

Using the information from the recharge model for the CTA, a simplistic water balance was calculated using the hydrologic equation of:

Inflow +/- Change in Storage = Outflow

The water balance showed that the dominant outflows are from evaporation which exceeds rainfall, and groundwater flowing out into Lake Dunstan. The dominant inflows were found to be precipitation and inflow of water from via the subsurface of the Pisa Range and fractures within the Otago Schist. From this water balance a total of 93 Mm^3/yr of water was calculated to pass through the CTA annually.

The typical method of allocating groundwater used in Otago by the O.R.C. is to allocate 50% of the natural precipitation that recharges the aquifer for abstraction. This is used so over-extraction of the groundwater resource won't occur. The natural precipitation that recharges the CTA from the Cromwell Flat and Pisa Range catchment was calculated to be 20 M m^3/yr. 50% of 20 Mm3/yr gives a volume of 10 Mm3/yr of groundwater that can be allocated for abstraction. Currently, only 3 Mm^3/yr is extracted, leaving 7 Mm^3/yr to be allocated. Since the Cromwell Flat has a relatively small land area, small population density and the availability of surface water (i.e. Lake Dunstan) it is unlikely that the total volume of 10 Mm^3/yr will be fully allocated.

6.6 Future Research

From the research carried during this study, there were a number areas where information was lacking that could help further improve the understanding of the CTA.

These recommendations for further research are:

- A larger spread of climate data from multiple climate stations across the Cromwell Flat and the Pisa Range is required to provide a better understanding of the seasonal changes the CTA experiences.
- A more detailed water chemistry analysis of CTA groundwater, Pisa Range streams, Pisa Range surface runoff and Lake Dunstan. This will identify any changes in groundwater quality, and allow comparison of the water chemistry of surface water from the Pisa Range with groundwater. Samples should be collected throughout a hydrological year to determine if there are any seasonal effects on the water chemistry of the CTA.
- A new stable isotopic analysis sampling program should be carried out with samples being collected from throughout a hydrological year to determine if there are any seasonal affects on the stable isotopic composition of groundwater and its recharge sources. More groundwater samples are required from the middle of Cromwell Flat, as there is a lack of data in this area of the Flat.

- Water samples of any subsurface water from the Pisa Range should be collected for water chemistry and stable isotopic analysis to help determine subsurface recharge from the Pisa Range.
- Pump tests should be carried out in bores located in the Luggate outwash gravels, and the Kawarau River and Clutha River derived Albert Town outwash gravels to determine if the hydrogeologic properties of the CTA changes between the different gravel units.
- Pump tests should be carried out near the lake margin with water samples being taken during pumping. These samples should be used for stable isotopic analysis to determine whether or not lake water is drawn into the aquifer during pumping.
- A more detailed groundwater level measurement program is required in more bores across the Cromwell Flat in addition to the ones monitored in this study. As many of the 41 bores in the O.R.C. database should be monitored. Measurements should be carried out more frequently (i.e. monthly). This will help determine if there are any subtle variations in the water table and if any seasonal fluctuations affect the groundwater table differently in other parts of the CTA.
- More Drilling and geophysics are required to help find the depth to the Tertiary sediments around the paleochannels. This will determine if there are any Tertiary sediment topographic highs that are above the groundwater table.

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Appendix 1.4.2

‘Descriptions of soils used in soils map (figure 1.3)’

Soil type	Description
Arrow – Alexandra soil (Steeplands)	Soils formed on the steep slopes of the Pisa Range directly on to the Otago Schist. These soils are very stony, have thin coverage and are susceptible to erosion from wind and water. Loess is common in these soils and Tunnel Gullying can occur. Typical description: Dark – greyish brown sandy loam and yellowish brown to pale olive brown sandy loam with schist gravel.
Letts steepland soil	Soils found on terrace scarps. Sourced from Tertiary sediments and Clutha derived alluvium. Thin loess cover is common. Typical description: Brown stony loam; with a very weakly developed medium nutty structure and yellowish brown very stony, loose, structureless loam.
Clare hill soils	Soils sourced from Hawkdun formation sediments. Found on rolling terrain. A massive claypan exists near the surface and may contain high soluble salt contents. Loess layers common. Typical description: Dark greyish brown stony sand to stony loam with pale brown stony sand and yellowish stony sandy clay (clay pan).
Clyde shallow soils	Occur on tops of older glacial outwash terraces. Found on the Lowburn terrace tops in the Cromwell area. A claypan is present near the surface and carbonate accumulation is common at this layer. Loess layers common. Typical description: Dark greyish brown friable sandy loam and yellowish brown friable gritty sandy loam.
Blackmans – Manungawera soils	Formed on schists and glacial outwash deposits. Found around the edge of the Cromwell Flat on the youngest terraces. These soils have very high concentrations of soluble salts. Typical description: Dark grey friable fine sandy loam and brown weakly compact sandy loam with a moderately developed fine and medium blocky structure.
Waenga soils	Found on alluvial fans and located at the back of the Cromwell Flat and up Burns Cottage rd gully. Typical description: Greyish brown loose to friable fine sandy loam and pale olive brown fine sandy loam.
Lochar soils	Formed from schist alluvium covered by loess. Found in Burns Cottage rd Gully. Typical description: Dark greyish brown sandy loam and brown to yellowish brown sandy loam with a pale olive brown firm heavy sandy loam.
Ripponvale soils	Formed on alluvial fans from terrace material. Found up Burns Cottage rd. Gully. Typical description: Greyish brown sandy loam and pale brownish grey to pale brown coarse sandy loam.
Molyneux soils	Formed from loess mixing with gravels and sands. Found on relatively smooth rolling terrain. Make up most the Cromwell Flat. Typical description: Dark brown loamy sand and yellowish brown gravel with a sandy matrix.

(Continued on next page)

Appendix 1.4.3 continued

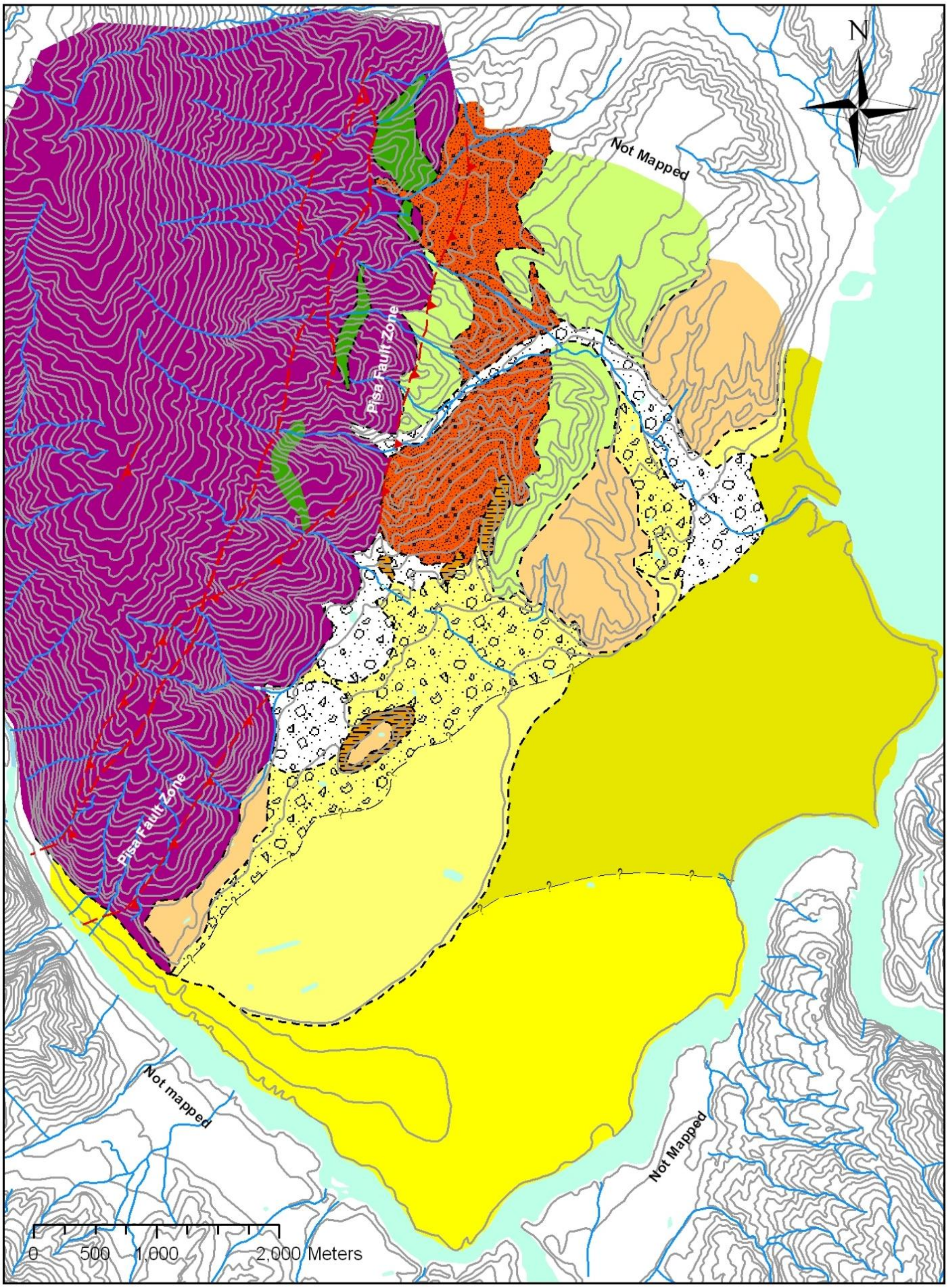
Lowburn soils	Formed from loess over outwash gravels. Found on Lindis outwash terrace tops. Calcium carbonate accumulation is common in the subsurface below a prominent clay pan. Typical description: Dark greyish brown friable gritty sandy loam with yellowish brown friable gritty sandy loam and yellowish brown sandy gravels and stones.
Cromwell sand	Sourced from flood deposits from the 1878 Clutha flood deposits. Sand was deposited across the Cromwell Flat via Aeolian processes. Has formed hummocky sand dune terrain. Typical description: Grey friable sand and pale olive grey very friable to loose sand with yellowish brown very friable loamy sand that is weakly compacted.

Descriptions from Leamy and Saunders (1967).

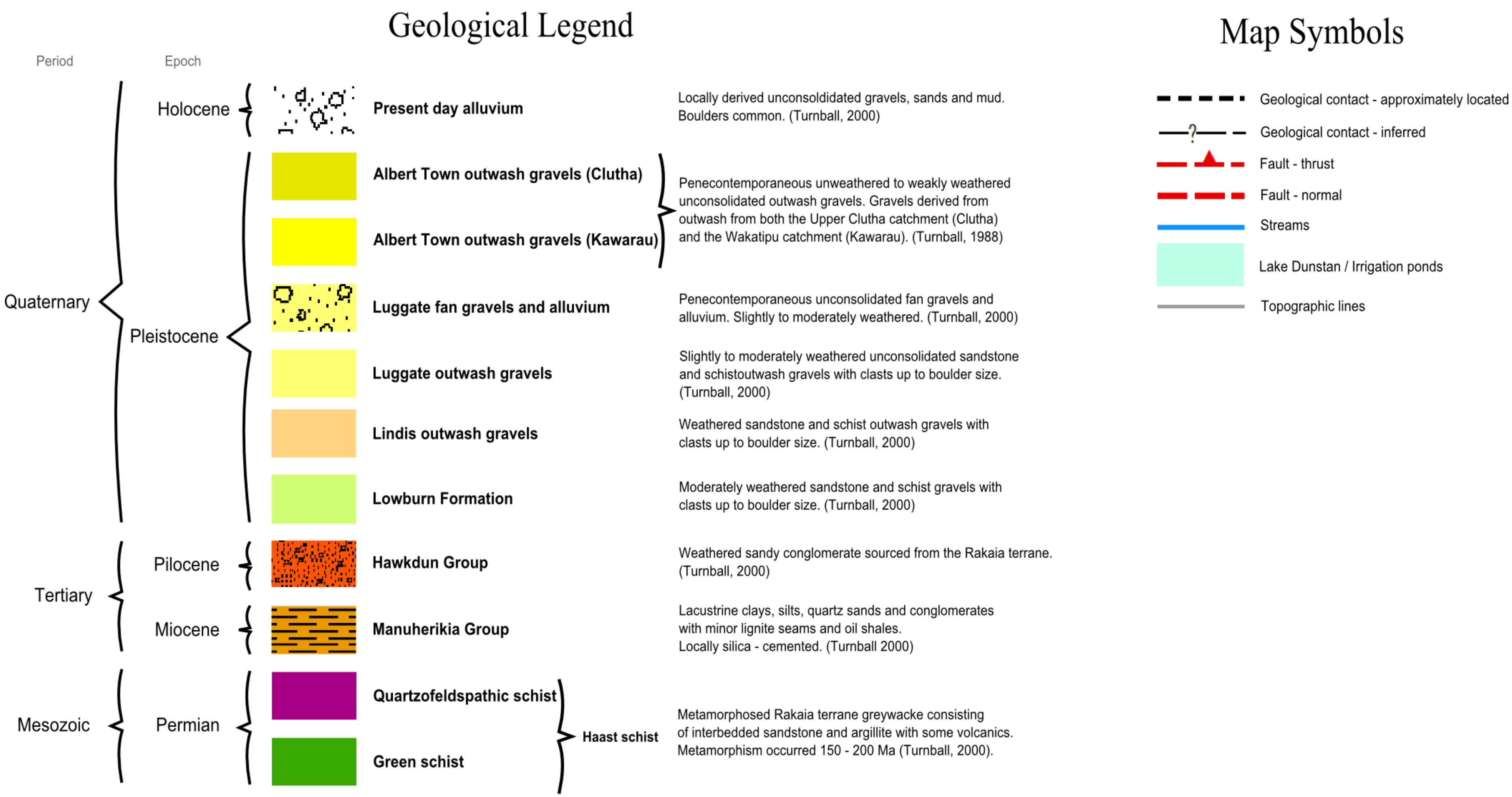
Appendix 2.3

'Geologic Map of the Cromwell Flat'

Geologic map modified fromTurnball (1988) and Turnball (2000)



Legend for geological map.



Appendix 3.2

'Flow rate calculations for Pisa Range Streams and site co ordinates'

Autumn – Time taken for stream to fill a 5 litre container

	Date	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Average time (s)	Flow rate L/s	Flow rate (m^3/s)
Site 017	11/05/2010	21.41	19.86	20.97	19.76	19.99		20.40	0.25	0.00025
Site 019	11/05/2010	22.88	21.43	19.25	17.89	17.09	17.15	18.56	0.27	0.00027
Site 035	13/05/2010	10.13	10.41	10.07	9.4	9.89	9.86	9.96	0.50	0.00050

Note: Site 017 - Waterfall on Leyser stream; Site 019 – Leyser Stream, measured at catch drum used to divert water away for irrigation - Test 1 dismissed as an outlier; Site 035 – Catch drum used for irrigation in Riches Gully stream, Flow rates may be higher due to rainfall in catchment 24 hrs before measurements were taken.

Average Autumn Stream flow rate (m^3/s)= (0.00025+0.00027+0.00050)/3
= 0.00034

(m^3/min) = 0.00034 x 60
= 0.0204
(m^3/hr) = 0.0204 x 60
= 1.224
(m^3/day) = 1.224 x 24
= 29.376
3 active streams = 29.376 x 3
= 88.128 (m^3/day)
(m^3/yr) = 88.128 x 365
= **32,166.72 (m^3/yr)**

(Continued over page)

Winter - Time taken for stream to fill a 5 litre container for Site 035 and time taken to fill a 2 litre container for Site 036.

	Date	Test 1	Test 2	Test 3	Test 4	Test 5	Average time (s)	Flow rate L/s	Flow rate (m^3/s)
Site 035	9/08/2010	12.05	11.64	13.74	12.75	12.7	12.576	0.40	0.00040
Site 036	9/08/2010	2.75	2.36	2.69	2.28	2.28	2.472	0.81	0.00081

Note: Site 035 – Catch drum used for irrigation in Riches Gully, Recent snow fall and rain 1 day previously to measurements; Site 036 – Snow's Gully stream, irrigation holding pond in flow.

Average Winter Stream flow rate (m^3/s) = (0.00040+0.00081)/2
= 0.00060

(m^3/min) = 0.00060 x 60
= 0.036
(m^3/hr) = 0.036 x 60
= 2.16
(m^3/day) = 2.16 x 24
= 51.84
3 active streams = 51.84 x 3
= 155.52 (m^3/day)
(m^3/yr) = 155.52 x 365
= **56,764.8 (m^3/yr)**

Site co ordinates

Site	Easting	Northing
Site 017	1297244	5006772
Site 019	1297371	5006681
Site 035	1296484	5005654
Site 036	1297079	5006258

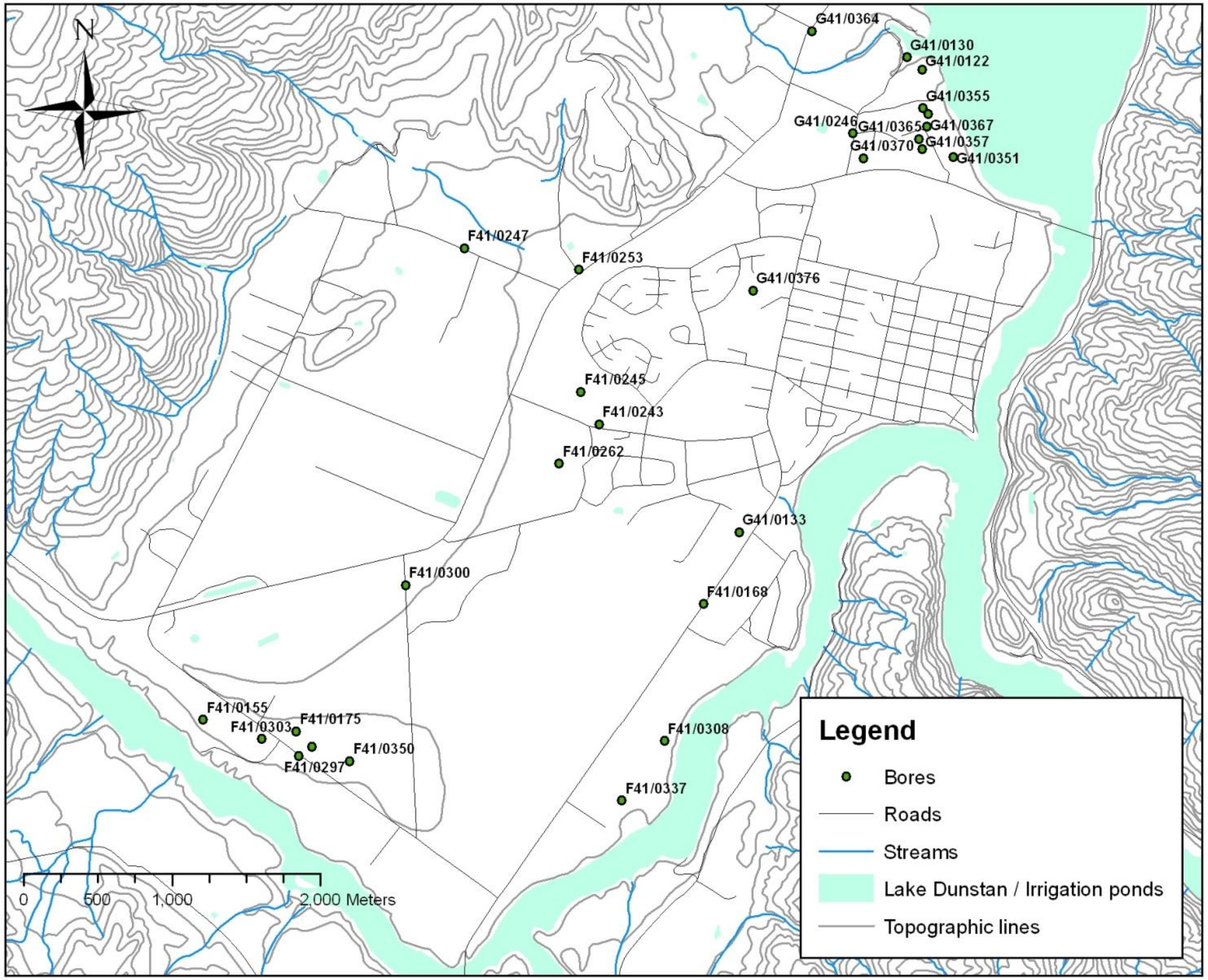
Appendix 3.3

‘Details and location map of bores used in hydrogeological cross-sections‘

Bore #	Type	Depth (m)	Diameter (m)	Elevation (m)	Easting	Northing	DTW (m)
F41/0155	Bore	37.0	-	231	1296645	5002627	-28.7
F41/0168	Bore	42.0	0.12	232	1299923	5003384	-18.86
F41/0175	Bore	40.0	0.13	221	1297256	5002551	-28.96
F41/0180	Bore	40.0	0.10	219	1297356	5002451	-33.35
F41/0243	Bore	35.0	0.17	217	1299240	5004559	-25
F41/0245	Bore	39.7	0.15	217	1299120	5004772	-22.8
F41/0247	Bore	38.4	0.13	239	1298357	5005711	-34.74
F41/0253	Bore	39.2	0.15	220	1299105	5005569	-24.3
F41/0262	Bore	45.0	0.08	217	1298977	5004302	-24.04
F41/0297	Bore	44.9	0.15	227	1297270	5002391	-29.54
F41/0300	Bore	48.7	0.13	240	1297971	5003508	-33.68
F41/0303	Bore	41.2	0.14	214	1297030	5002502	-29
F41/0308	Bore	29.4	0.13	199	1299667	5002490	-21.2
F41/0337	Bore	17.2	0.15	212	1299388	5002100	-21.39
F41/0350	Bore	42.9	0.30	218	1297605	5002356	-28.78
G41/0122	Bore	24.1	0.13	227	1302071	5005654	-15.8
G41/0130	Bore	7.1	0.10	227	1301255	5006959	-1.94
G41/0133	Bore	19.0	0.05	206	1300157	5003855	-16.5
G41/0246	Bore	37.2	0.30	199	1300901	5006461	-14.6
G41/0349	Bore	26.4	0.13	198	1301394	5006588	-6.13
G41/0351	Bore	26.3	0.13	210	1301558	5006306	-11.05
G41/0355	Bore	30.3	0.13	210	1301359	5006625	-15
G41/0357	Bore	24.2	0.13	199	1301356	5006358	-13.64
G41/0364	Bore	28.2	0.15	209	1300635	5007130	-17.77
G41/0365	Bore	30.1	0.13	214	1301333	5006424	-15.18
G41/0367	Bore	28.7	0.13	209	1301385	5006505	-13.95
G41/0370	Bore	29.8	0.15	224	1300973	5006300	-15.75
G41/0376	Bore	26.0	0.38	216	1300248	5005434	-12.38

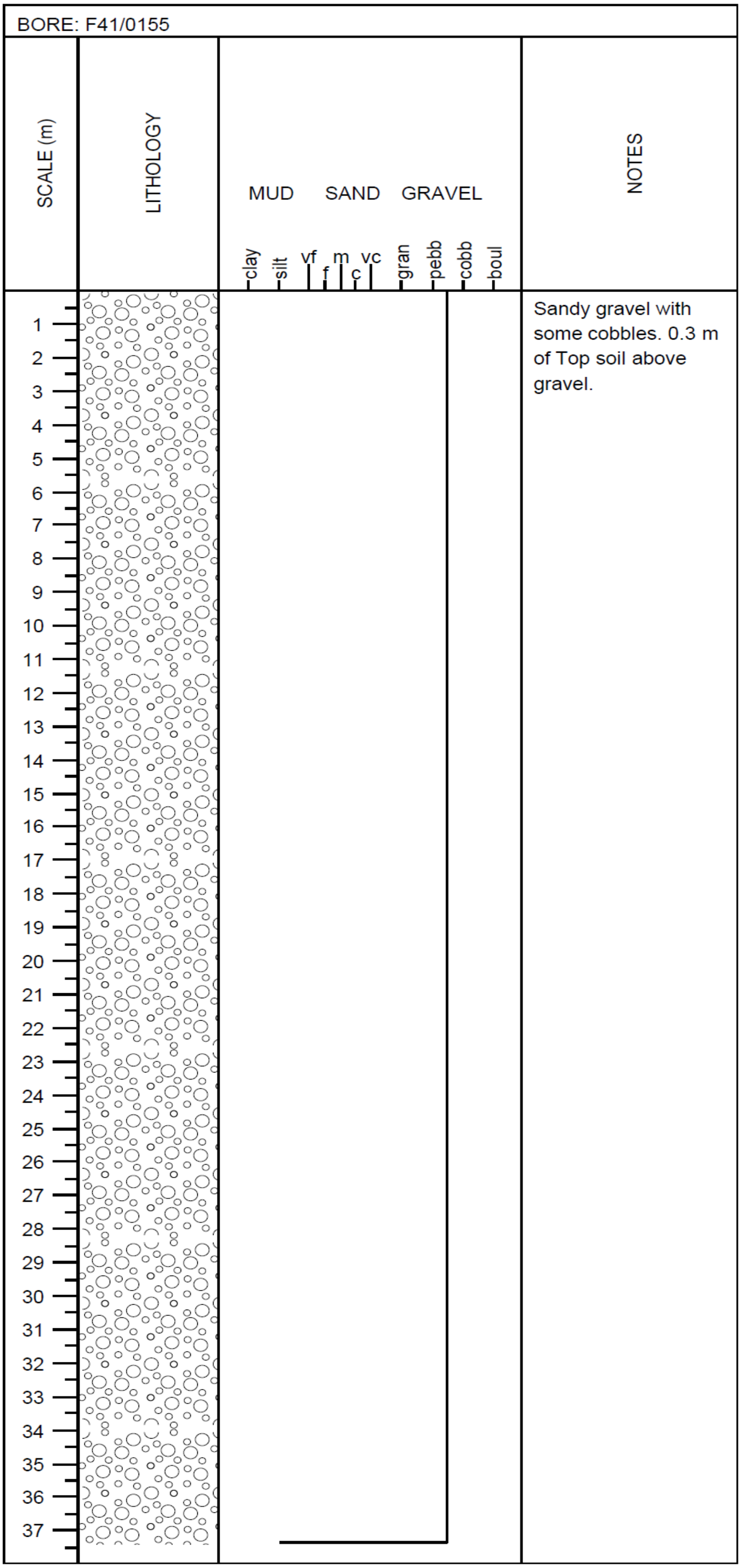
Note: DTW (Depth To Water) – DTW (from surface) values gathered from O.R.C. database (2010a).

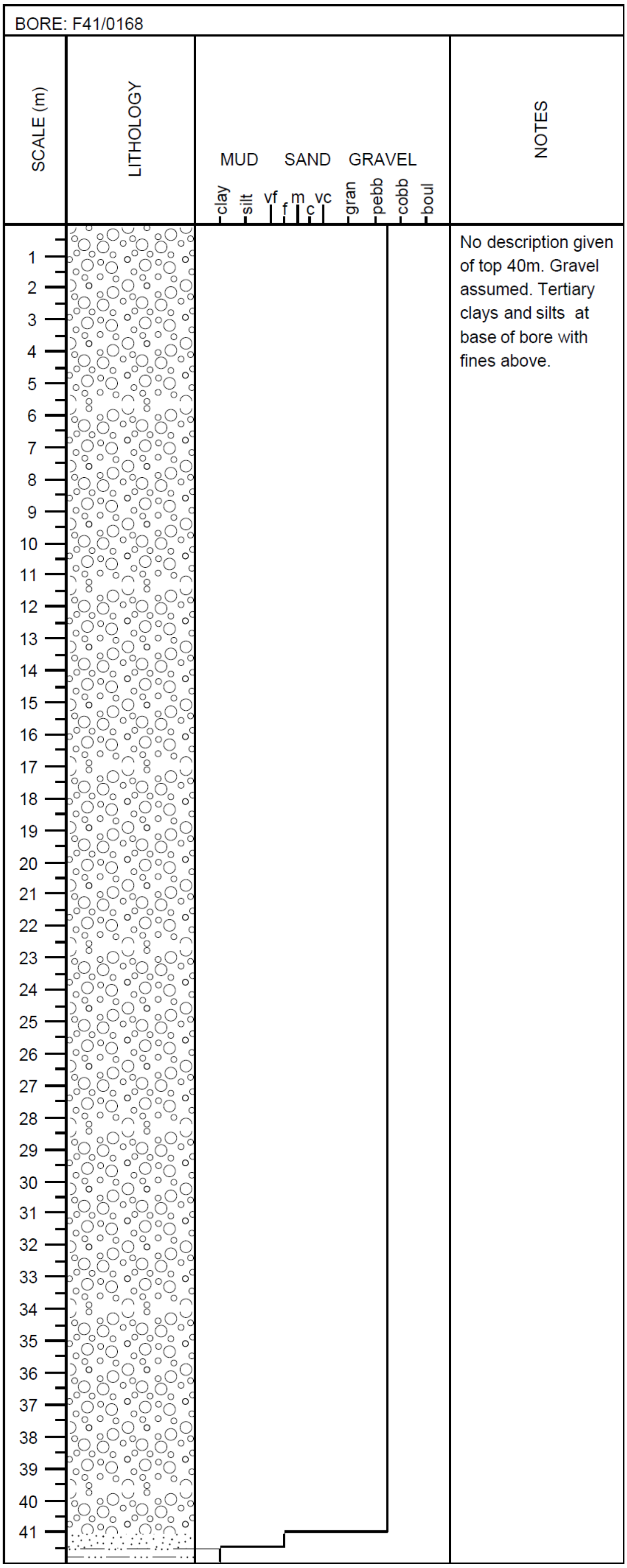
Map of bore locations used in hydrogeological cross-sections

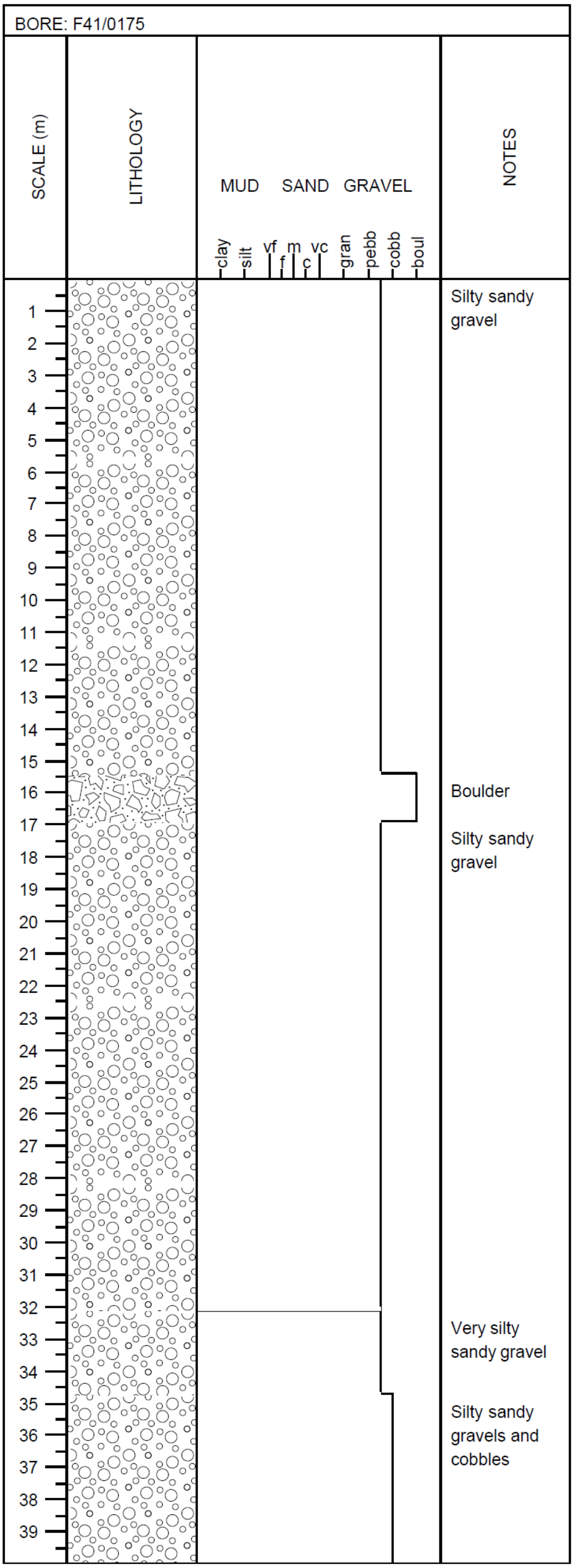


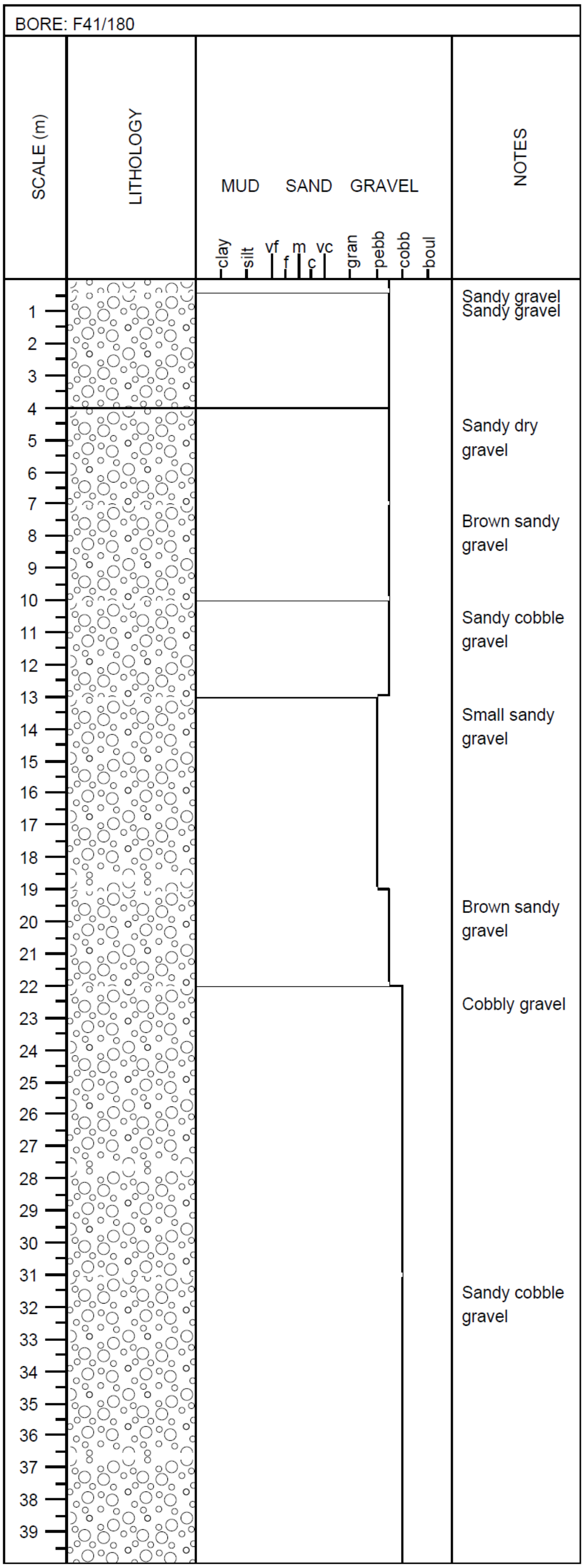
Appendix 3.3.1

‘Physical geologic descriptions of bore logs used in hydrogeological cross-sections’


BORE: F41/0155
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Sandy gravel with some cobbles. 0.3 m of Top soil above gravel.


BORE: F41/0168
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
No description given of top 40m. Gravel assumed. Tertiary clays and silts at base of bore with fines above.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41


BORE: F41/0175
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
Silty sandy gravel
Boulder
Silty sandy gravel
Very silty sandy gravel
Silty sandy gravels and cobbles


BORE: F41/180
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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34
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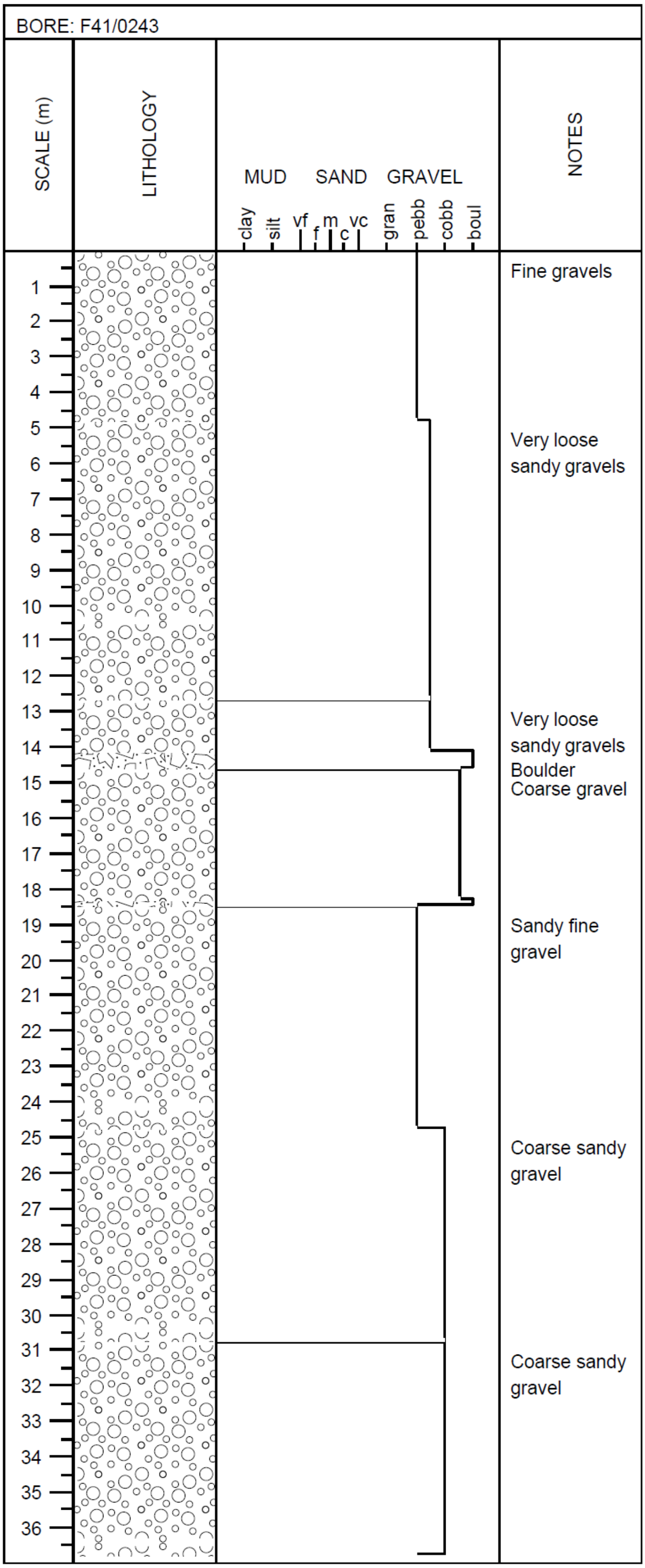
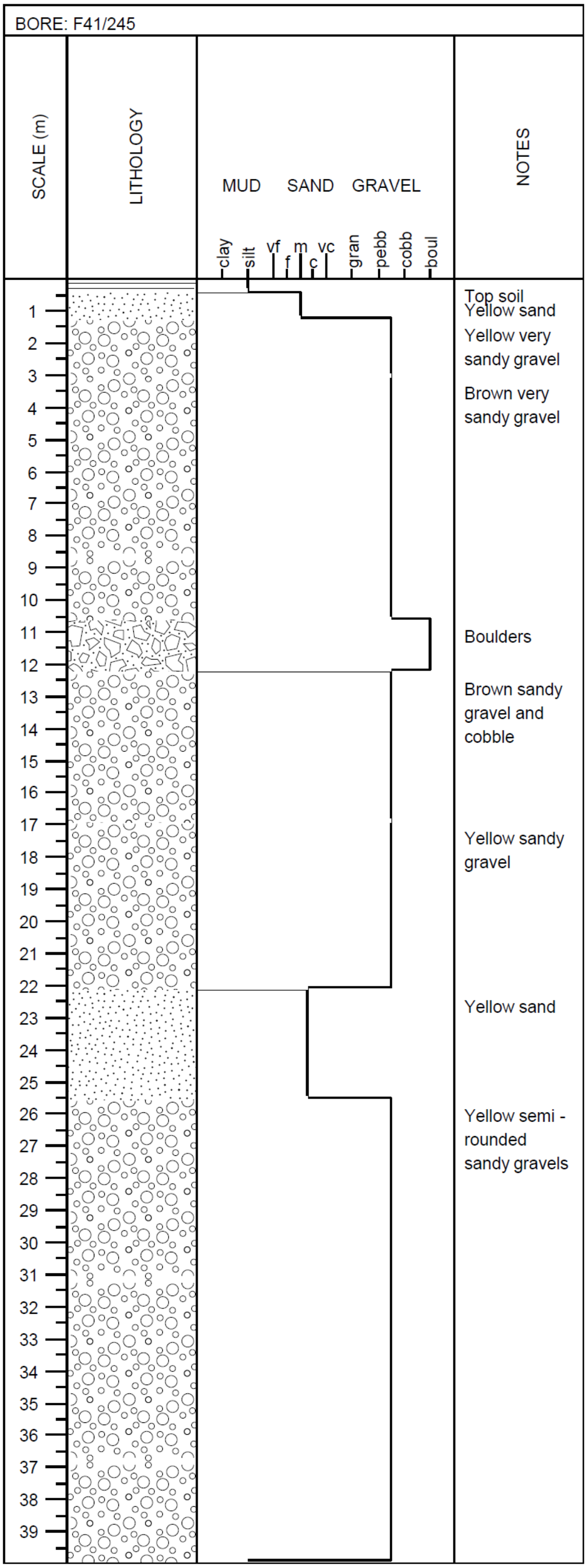
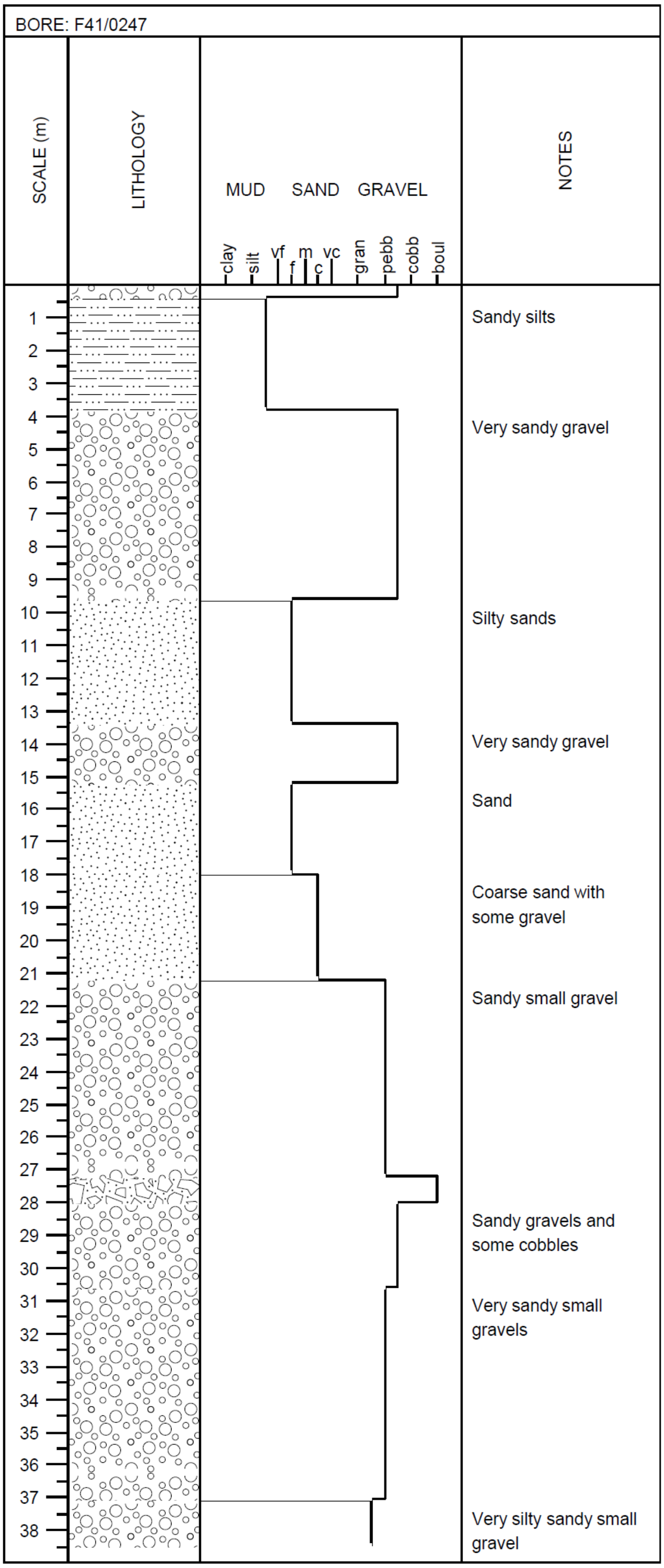
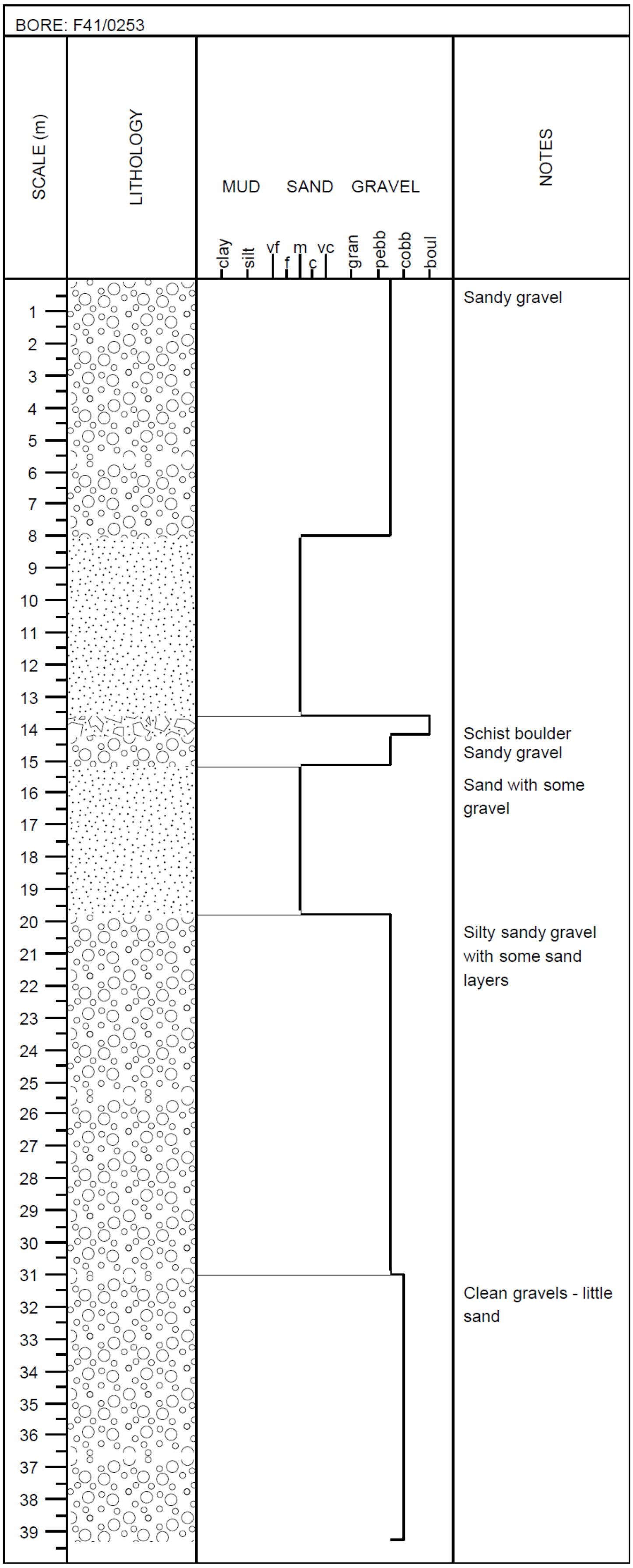
36
37
38
39
Sandy gravel
Sandy gravel
Sandy dry gravel
Brown sandy gravel
Sandy cobble gravel
Small sandy gravel
Brown sandy gravel
Cobbly gravel
Sandy cobble gravel

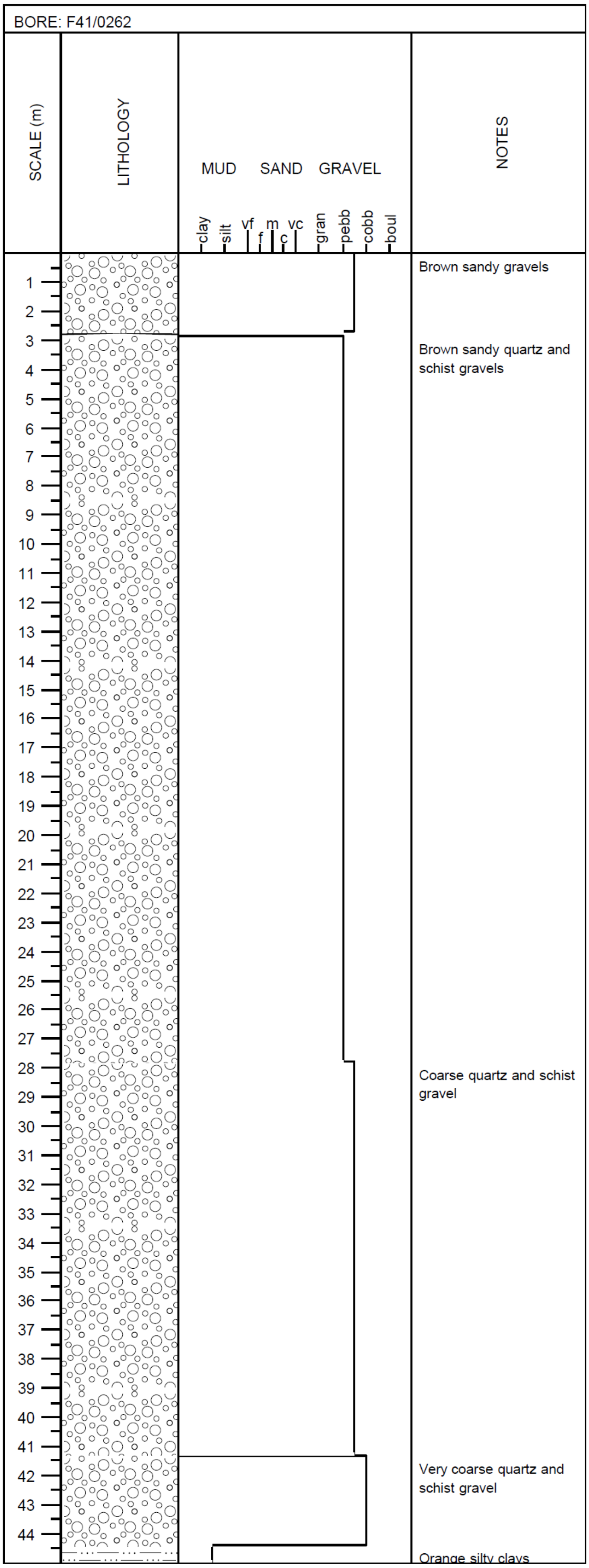

BORE: F41/0243
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
Fine gravels
Very loose sandy gravels
Very loose sandy gravels
Boulder
Coarse gravel
Sandy fine gravel
Coarse sandy gravel
Coarse sandy gravel

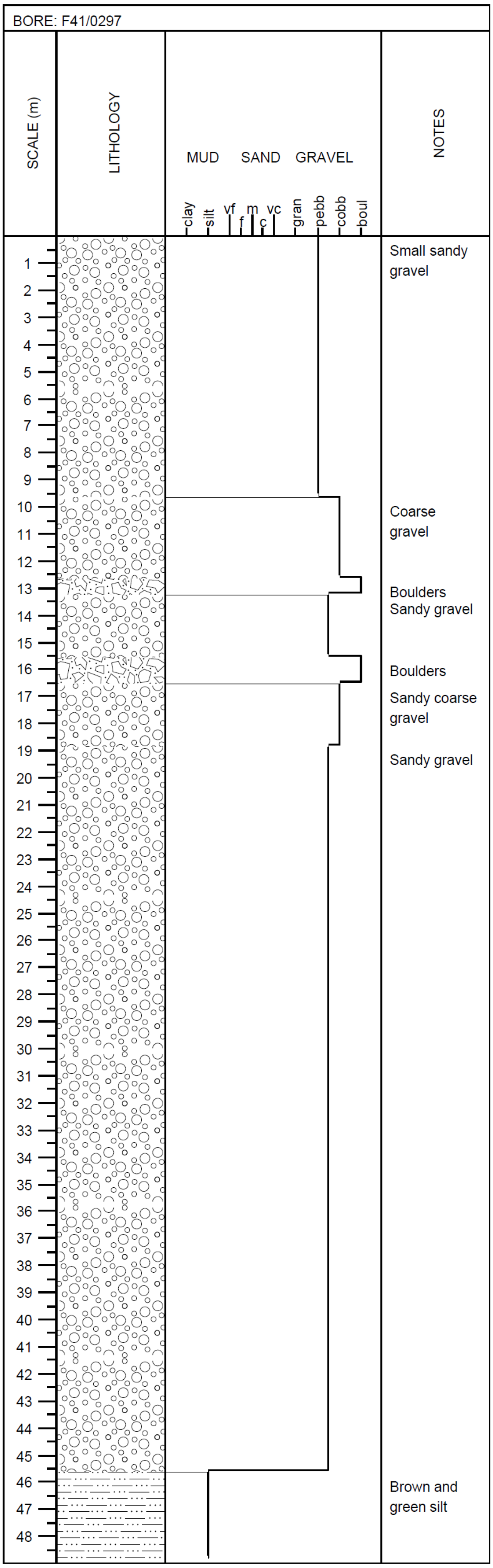

BORE: F41/245
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
Top soil
Yellow sand
Yellow very sandy gravel
Brown very sandy gravel
Boulders
Brown sandy gravel and cobble
Yellow sandy gravel
Yellow sand
Yellow semi - rounded sandy gravels

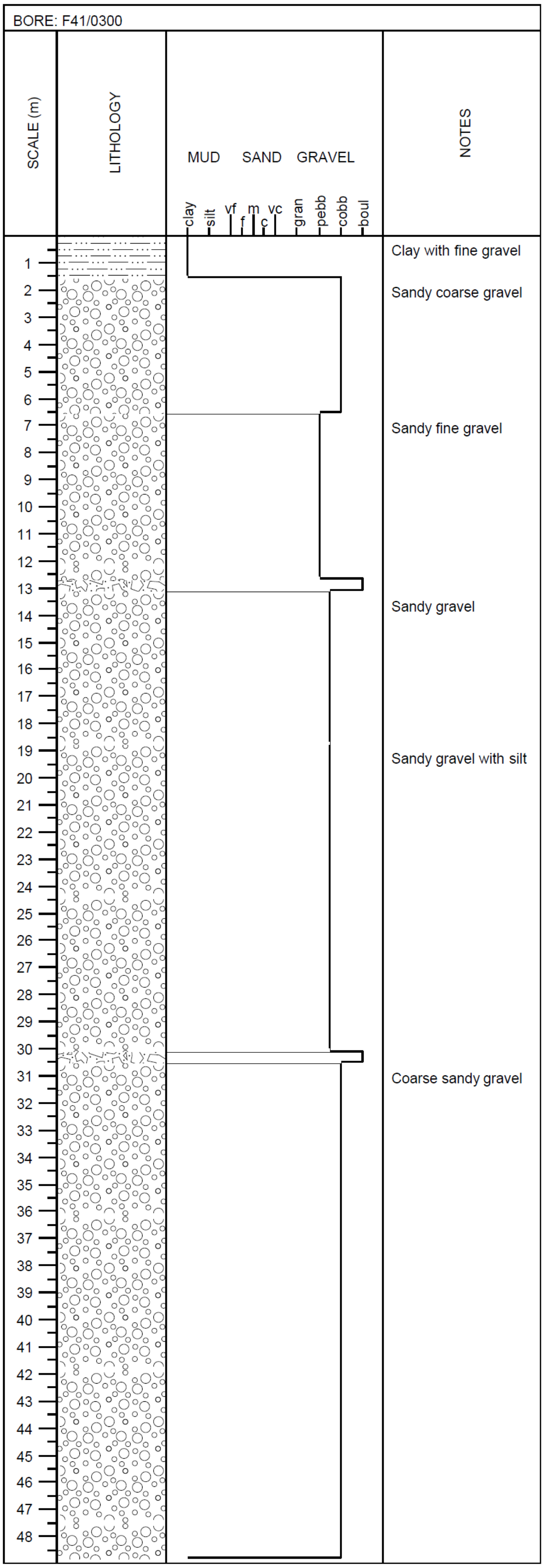

BORE: F41/0247
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Sandy silts
Very sandy gravel
Silty sands
Very sandy gravel
Sand
Coarse sand with some gravel
Sandy small gravel
Sandy gravels and some cobbles
Very sandy small gravels
Very silty sandy small gravel

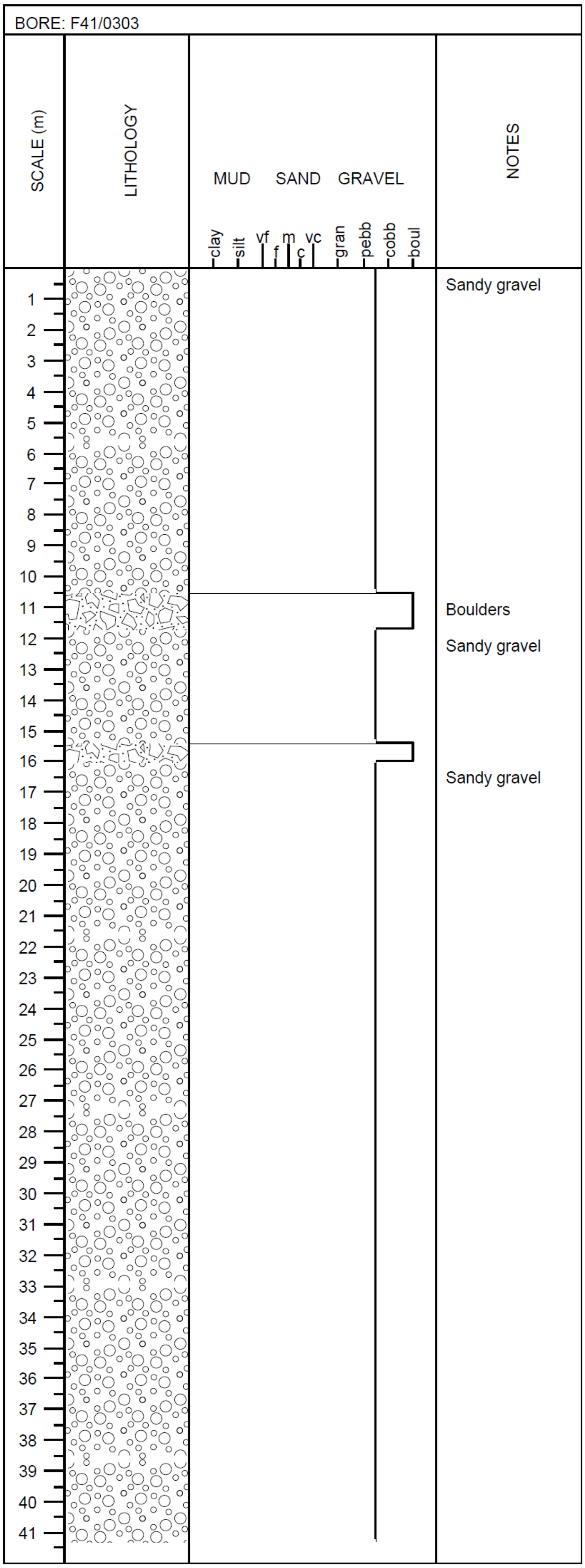


BORE: F41/0253
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
Sandy gravel
Schist boulder
Sandy gravel
Sand with some gravel
Silty sandy gravel with some sand layers
Clean gravels - little sand


BORE: F41/0262
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
Brown sandy gravels
Brown sandy quartz and schist gravels
Coarse quartz and schist gravel
Very coarse quartz and schist gravel
Orange silty clays


BORE: F41/0297
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
Small sandy gravel
Coarse gravel
Boulders
Sandy gravel
Boulders
Sandy coarse gravel
Sandy gravel
Brown and green silt


BORE: F41/0300
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
Clay with fine gravel
Sandy coarse gravel
Sandy fine gravel
Sandy gravel
Sandy gravel with silt
Coarse sandy gravel


BORE: F41/0303
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
Sandy gravel
Boulders
Sandy gravel
Sandy gravel
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11
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16
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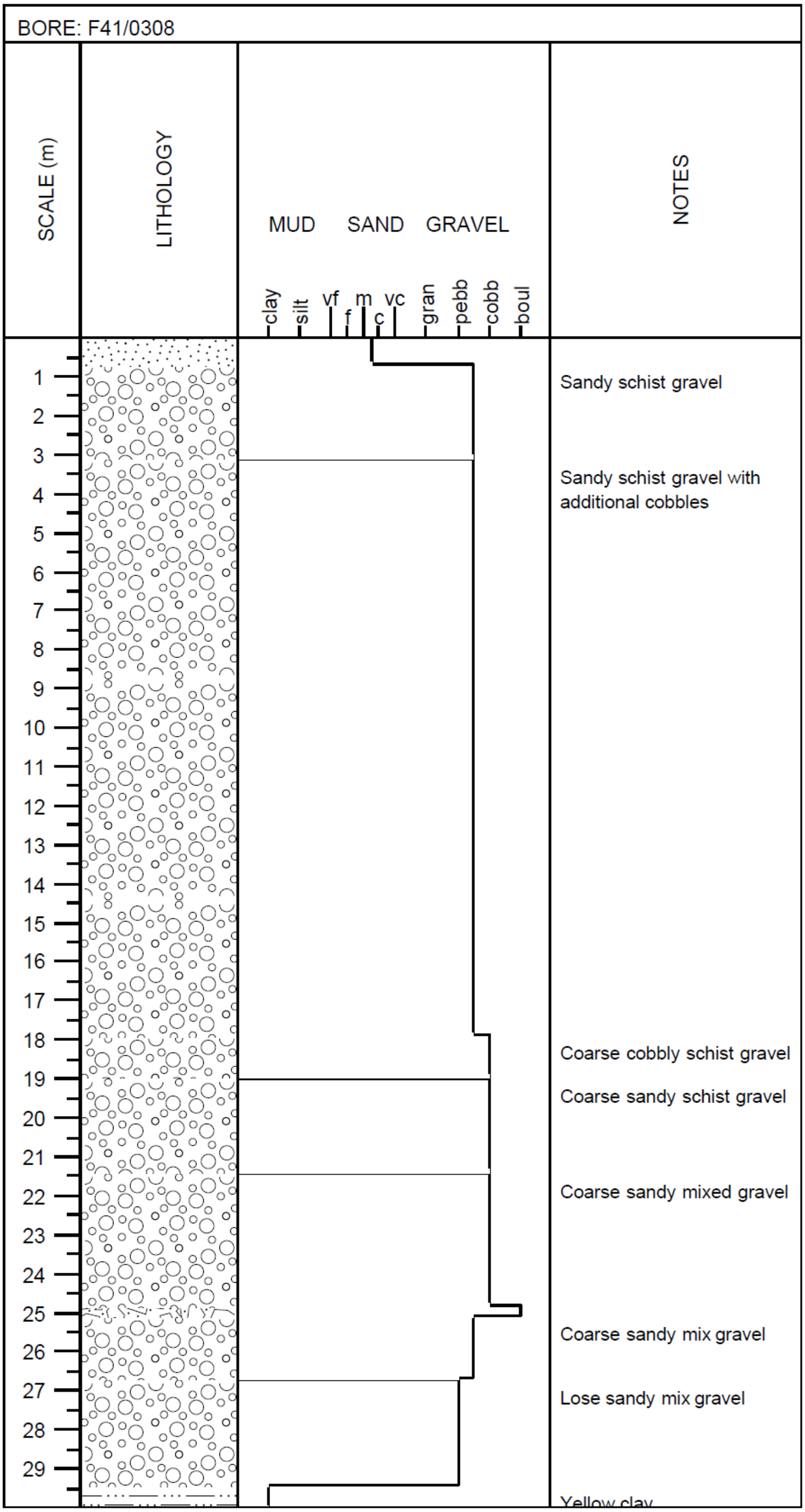
41


BORE: F41/0308
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
1
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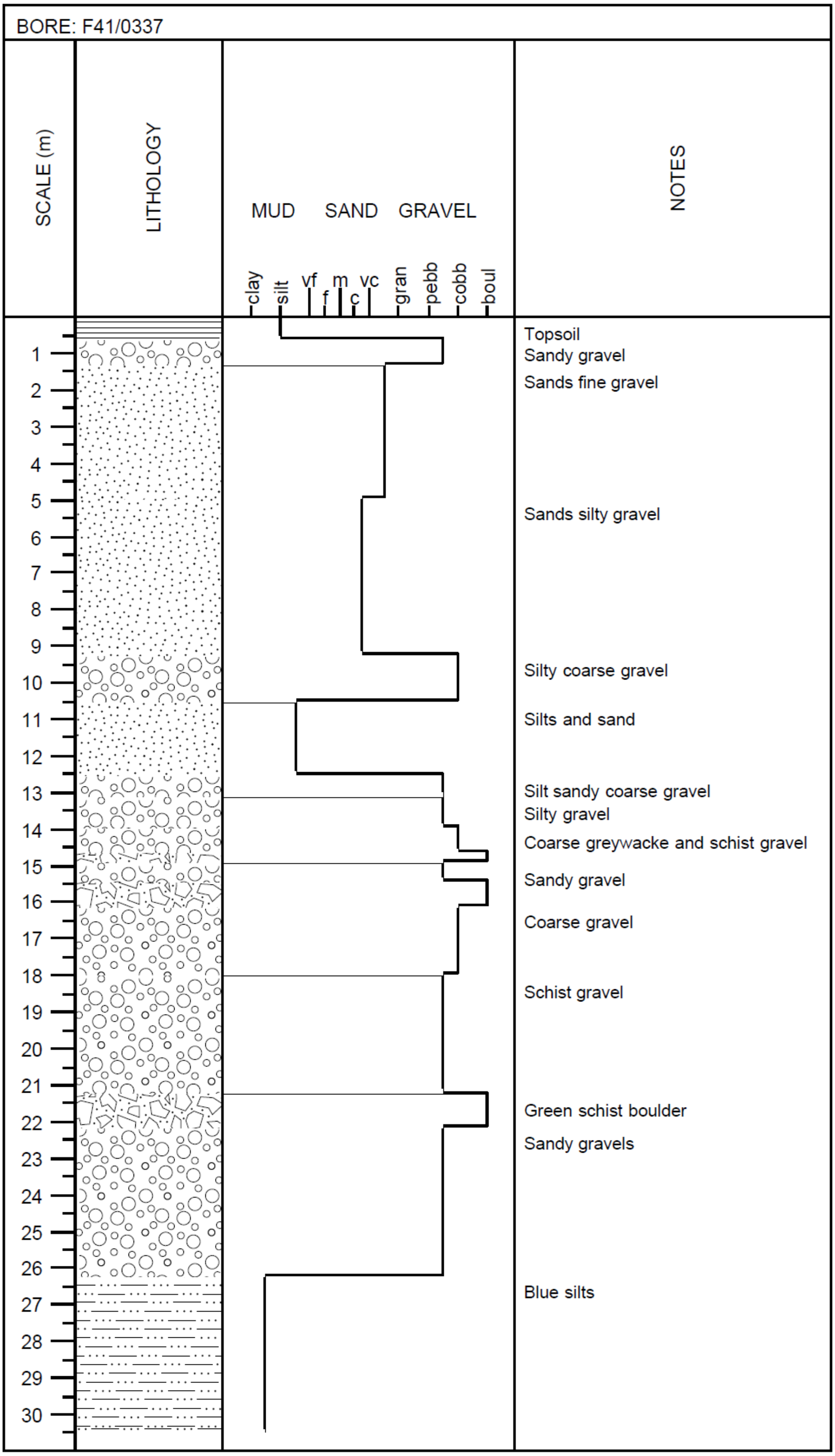
26
27
28
29
Sandy schist gravel
Sandy schist gravel with additional cobbles
Coarse cobbly schist gravel
Coarse sandy schist gravel
Coarse sandy mixed gravel
Coarse sandy mix gravel
Lose sandy mix gravel
Yellow clay


BORE: F41/0337
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
Topsoil
Sandy gravel
Sands fine gravel
Sands silty gravel
Silty coarse gravel
Silts and sand
Silt sandy coarse gravel
Silty gravel
Coarse greywacke and schist gravel
Sandy gravel
Coarse gravel
Schist gravel
Green schist boulder
Sandy gravels
Blue silts
1
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6
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8
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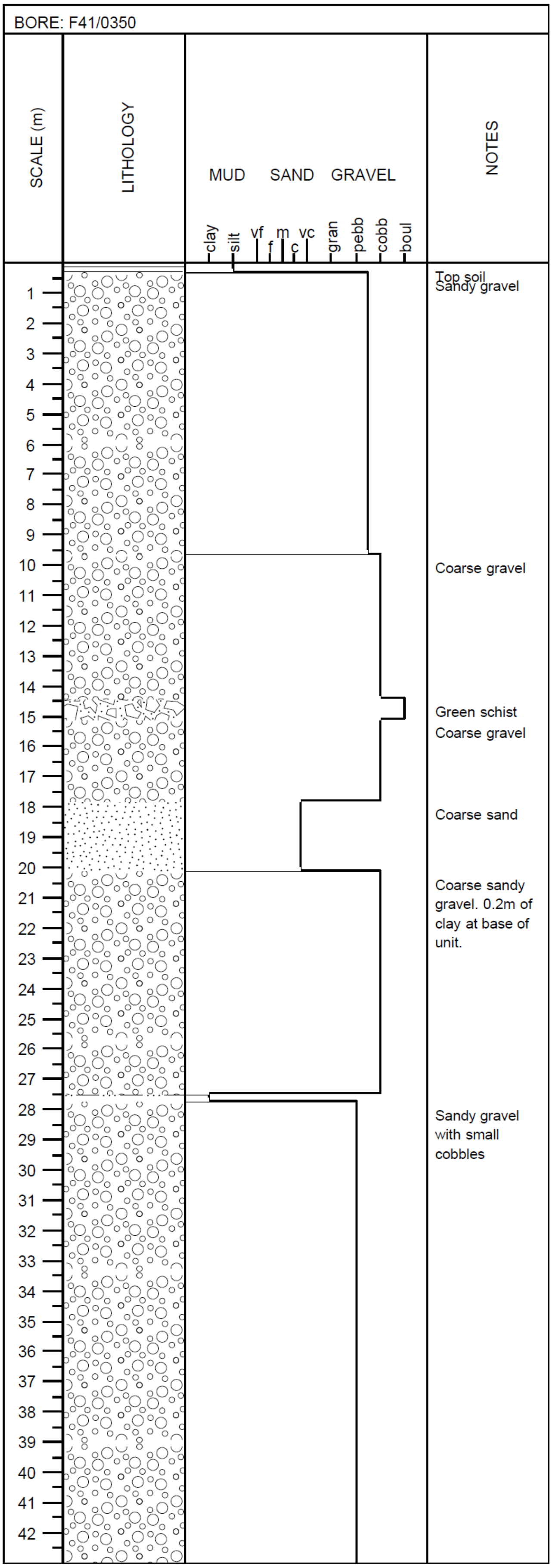
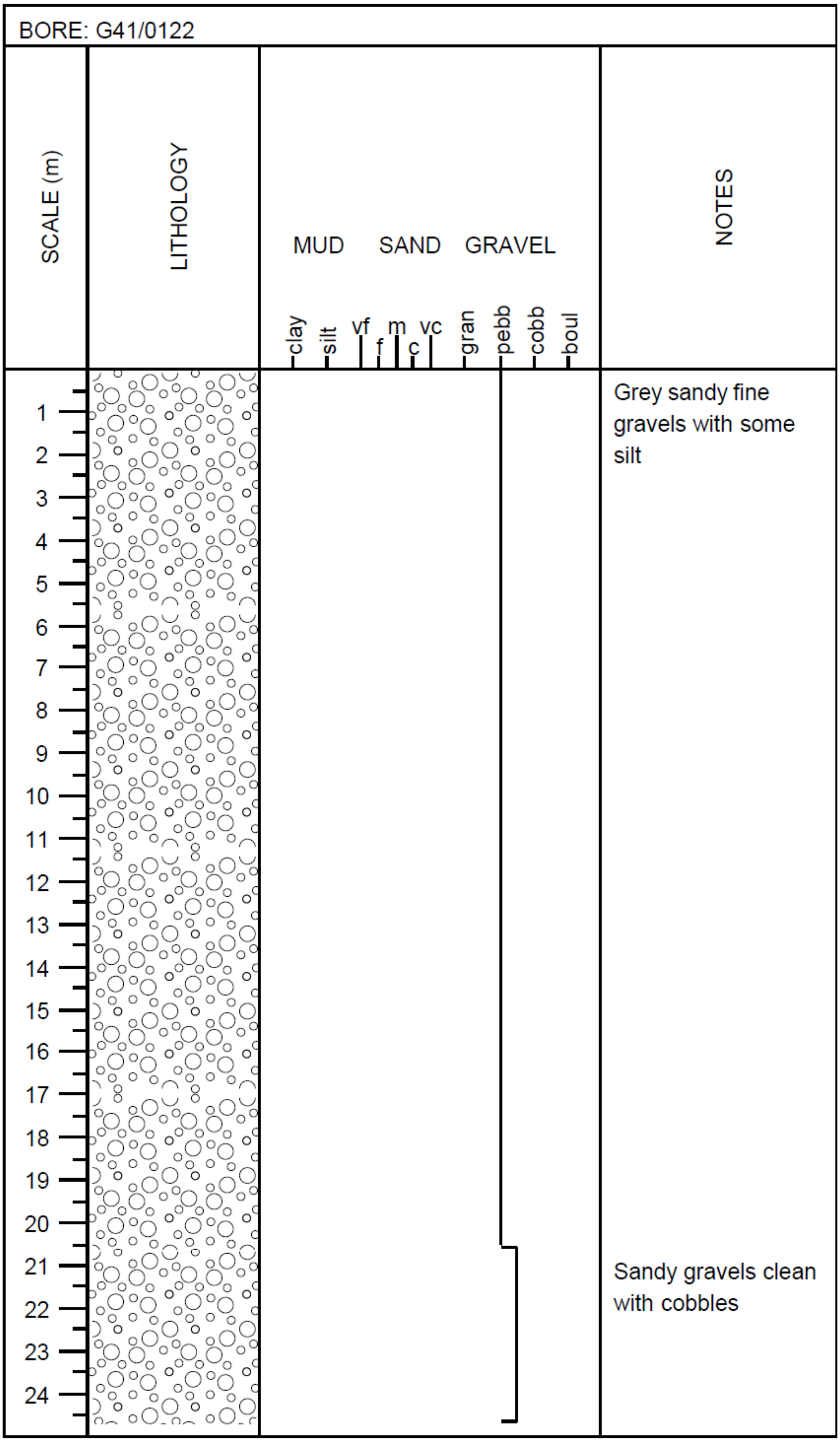

BORE: F41/0350
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42
Top soil
Sandy gravel
Coarse gravel
Green schist
Coarse gravel
Coarse sand
Coarse sandy gravel. 0.2m of clay at base of unit.
Sandy gravel with small cobbles


BORE: G41/0122
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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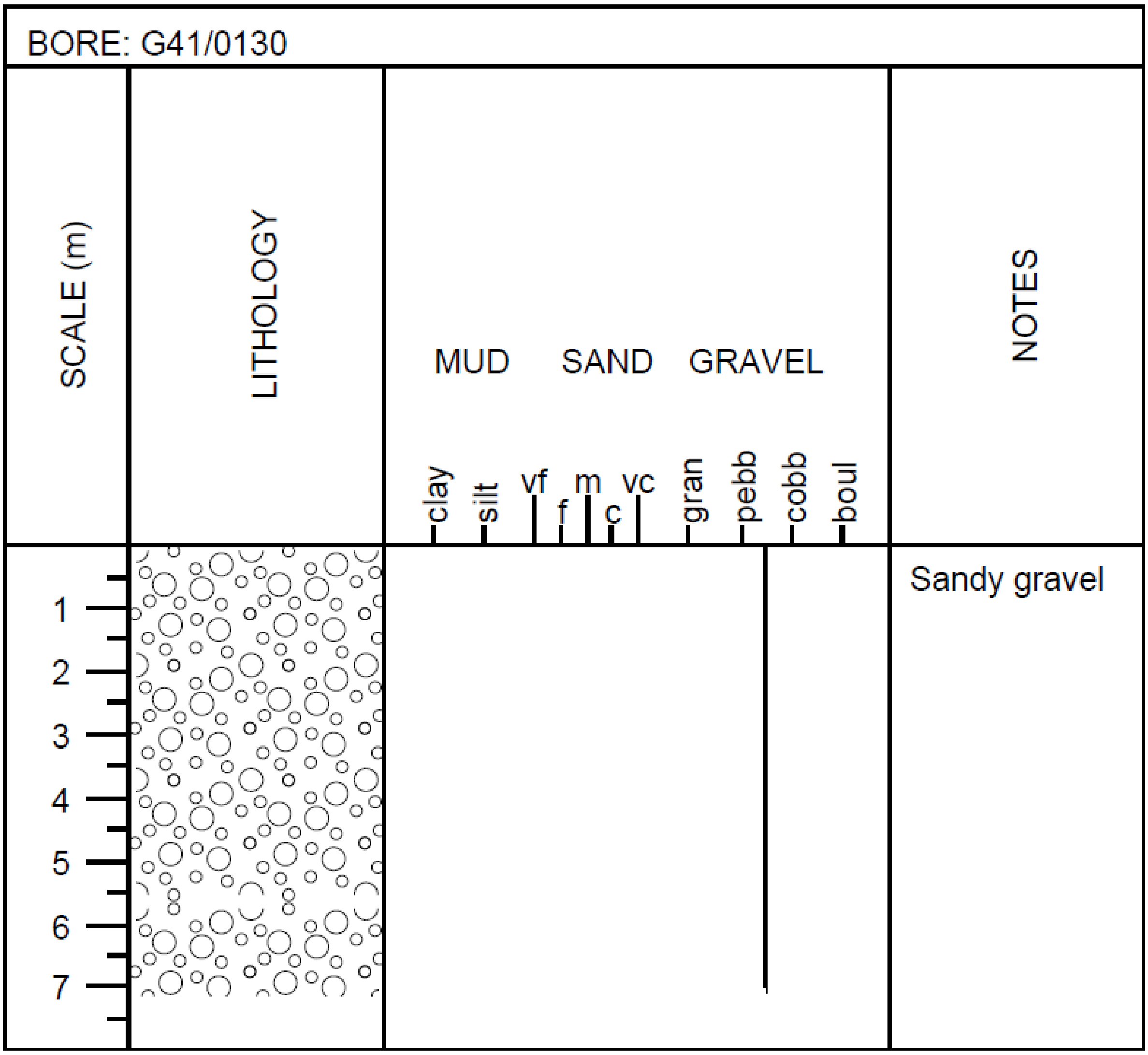
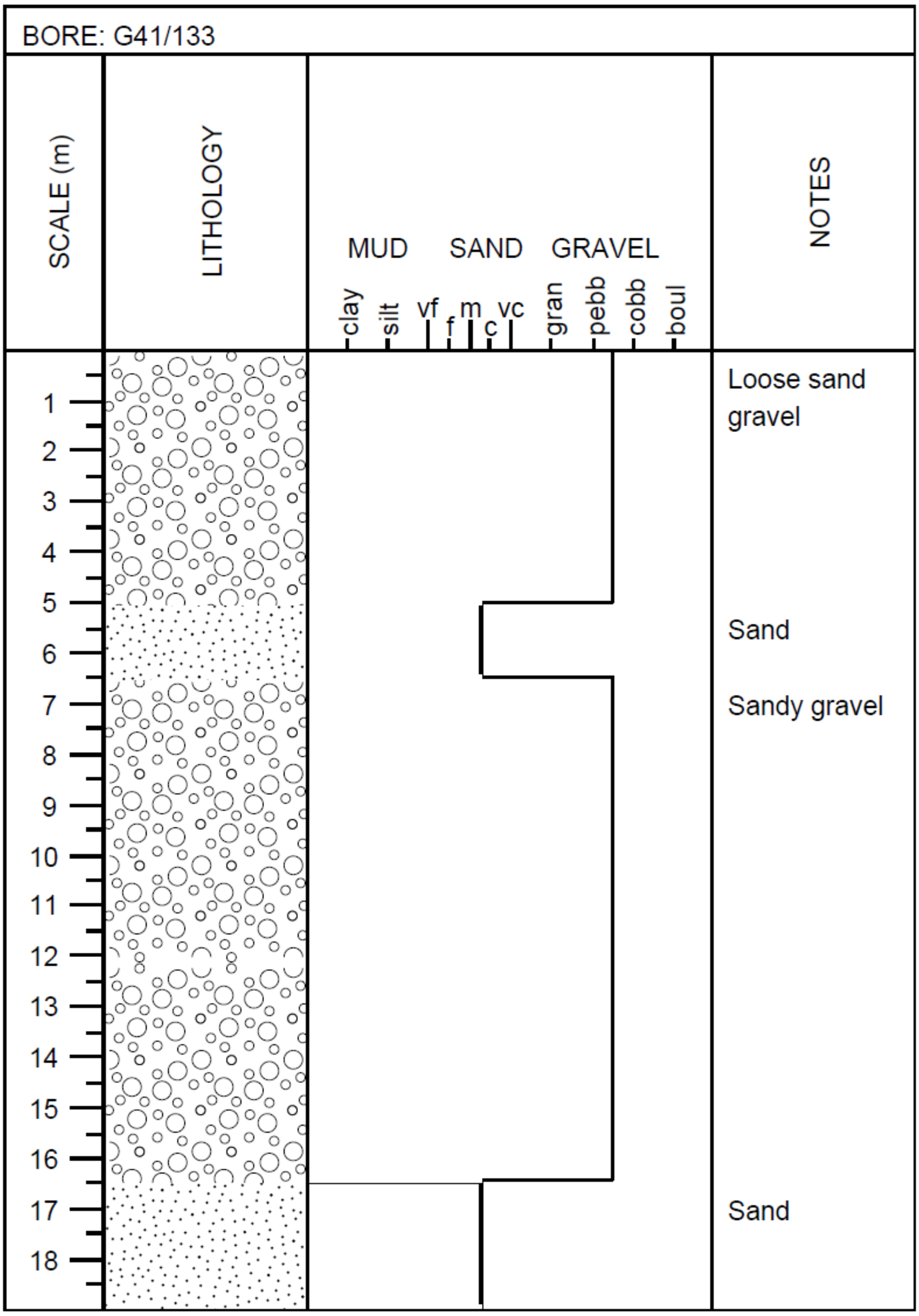
19
20
21
22
23
24
Grey sandy fine gravels with some silt
Sandy gravels clean with cobbles



BORE: G41/0130
SCALE (m)
LITHOLOGY
MUD
SAND
GRAVEL
NOTES
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
1
2
3
4
5
6
7
Sandy gravel


BORE: G41/133
SCALE (m)
LITHOLOGY
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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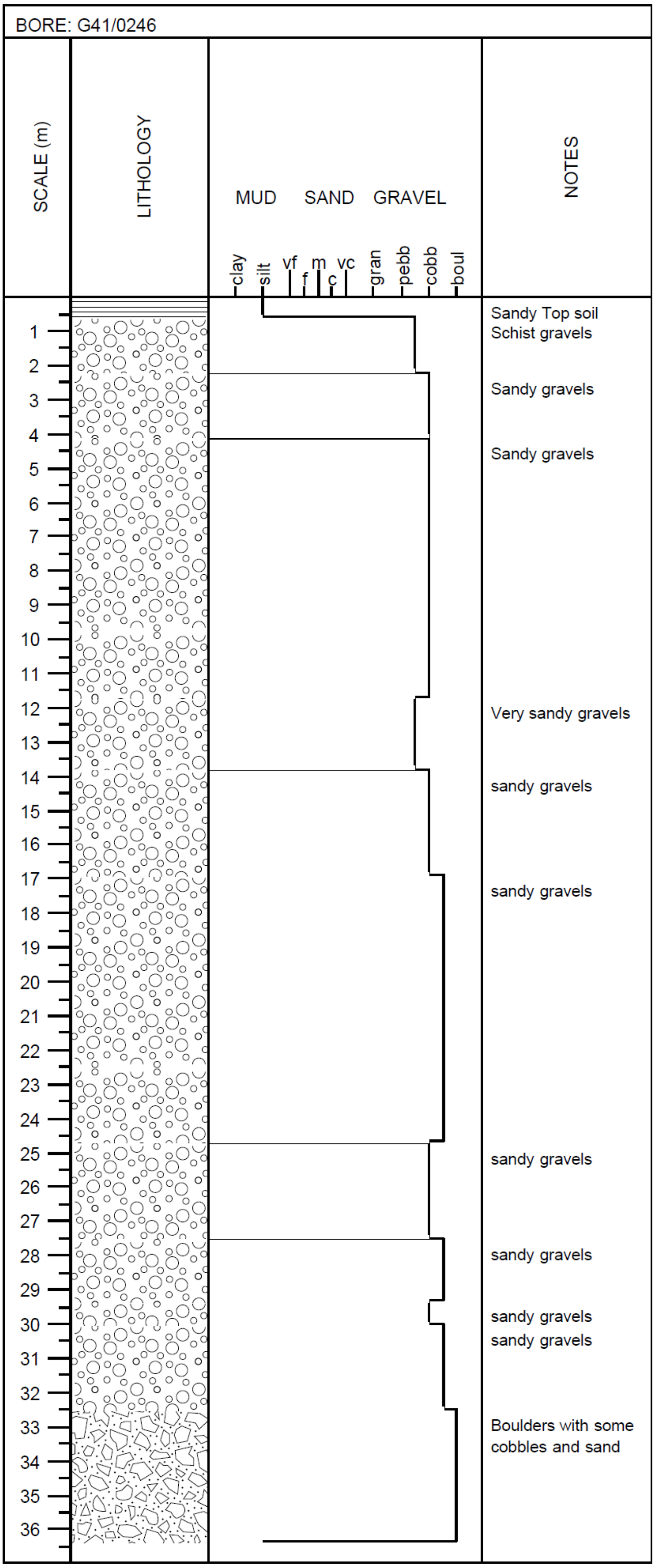
16
17
18
Loose sand gravel
Sand
Sandy gravel
Sand


BORE: G41/0246
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
1
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31
32
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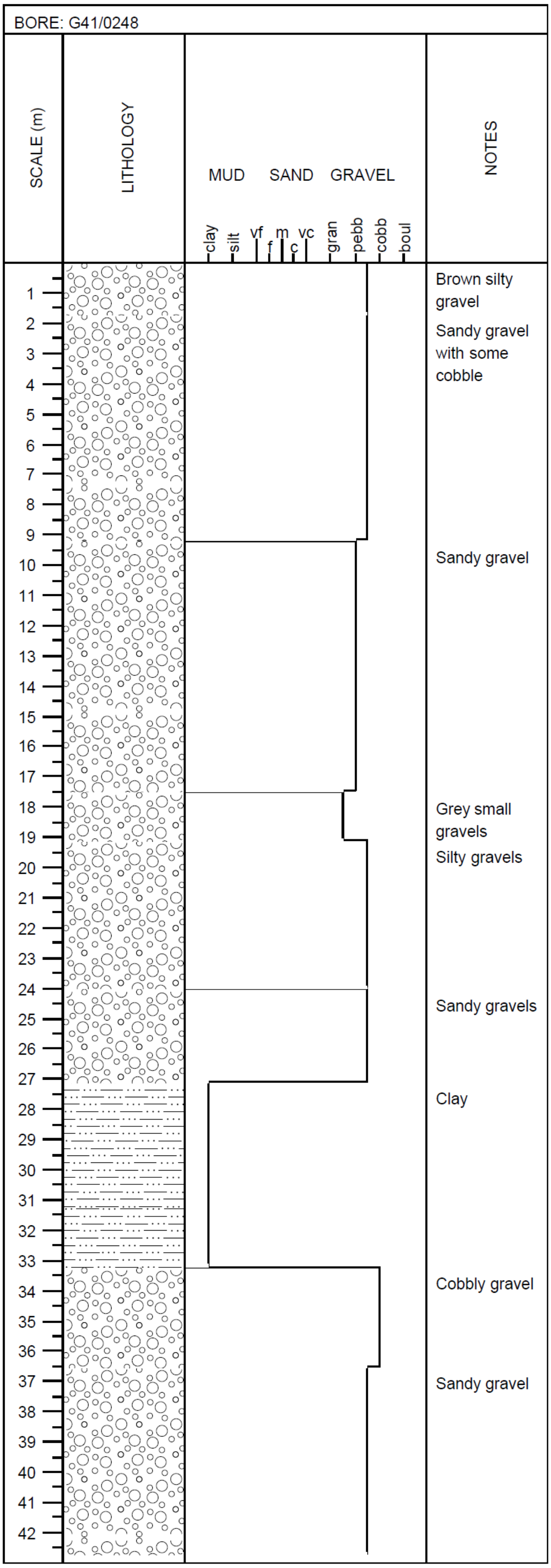
34
35
36
Sandy Top soil
Schist gravels
Sandy gravels
Sandy gravels
Very sandy gravels
sandy gravels
sandy gravels
sandy gravels
sandy gravels
sandy gravels
sandy gravels
Boulders with some cobbles and sand


BORE: G41/0248
SCALE (m)
LITHOLOGY
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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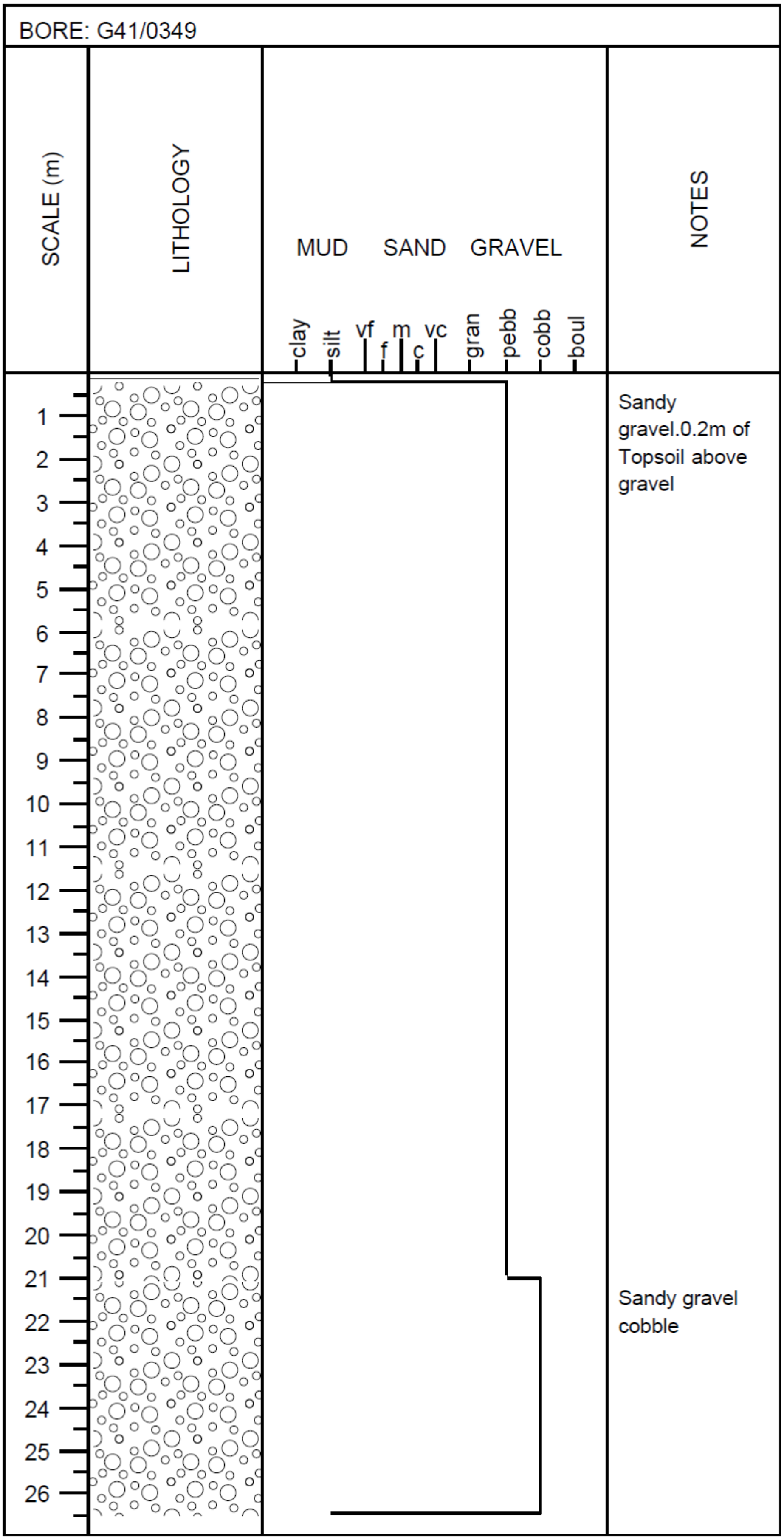
41
42
Brown silty gravel
Sandy gravel with some cobble
Sandy gravel
Grey small gravels
Silty gravels
Sandy gravels
Clay
Cobbly gravel
Sandy gravel


BORE: G41/0349
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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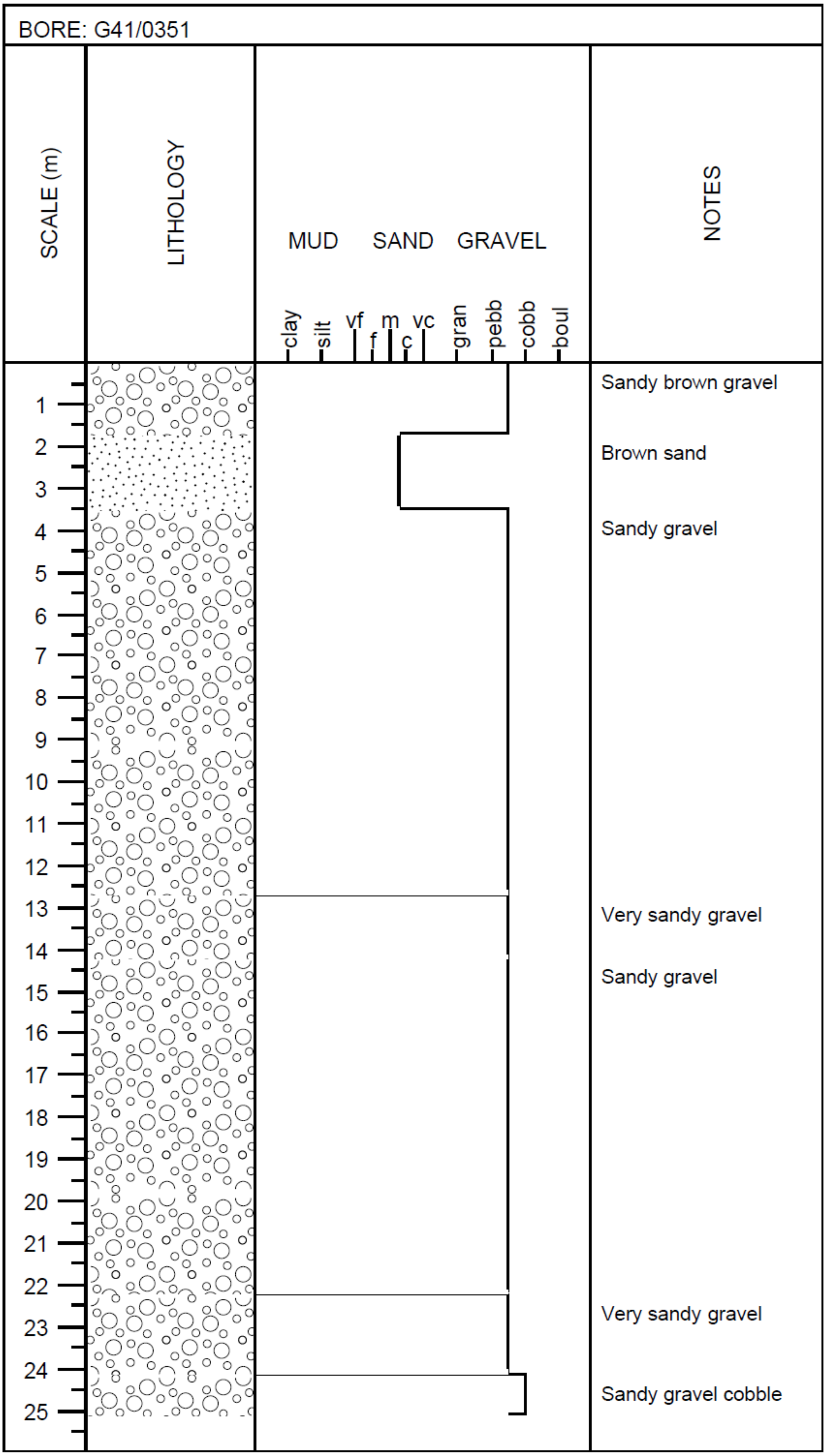
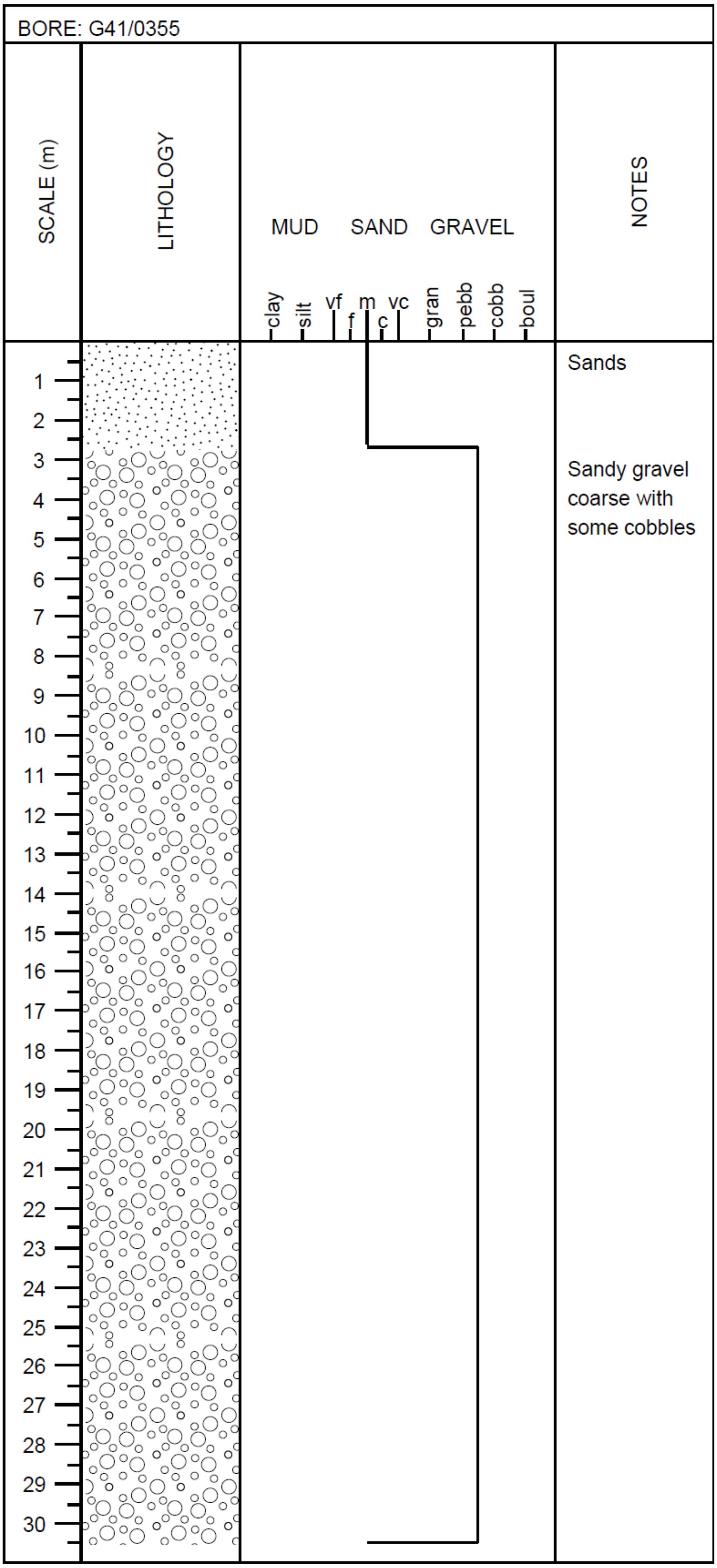
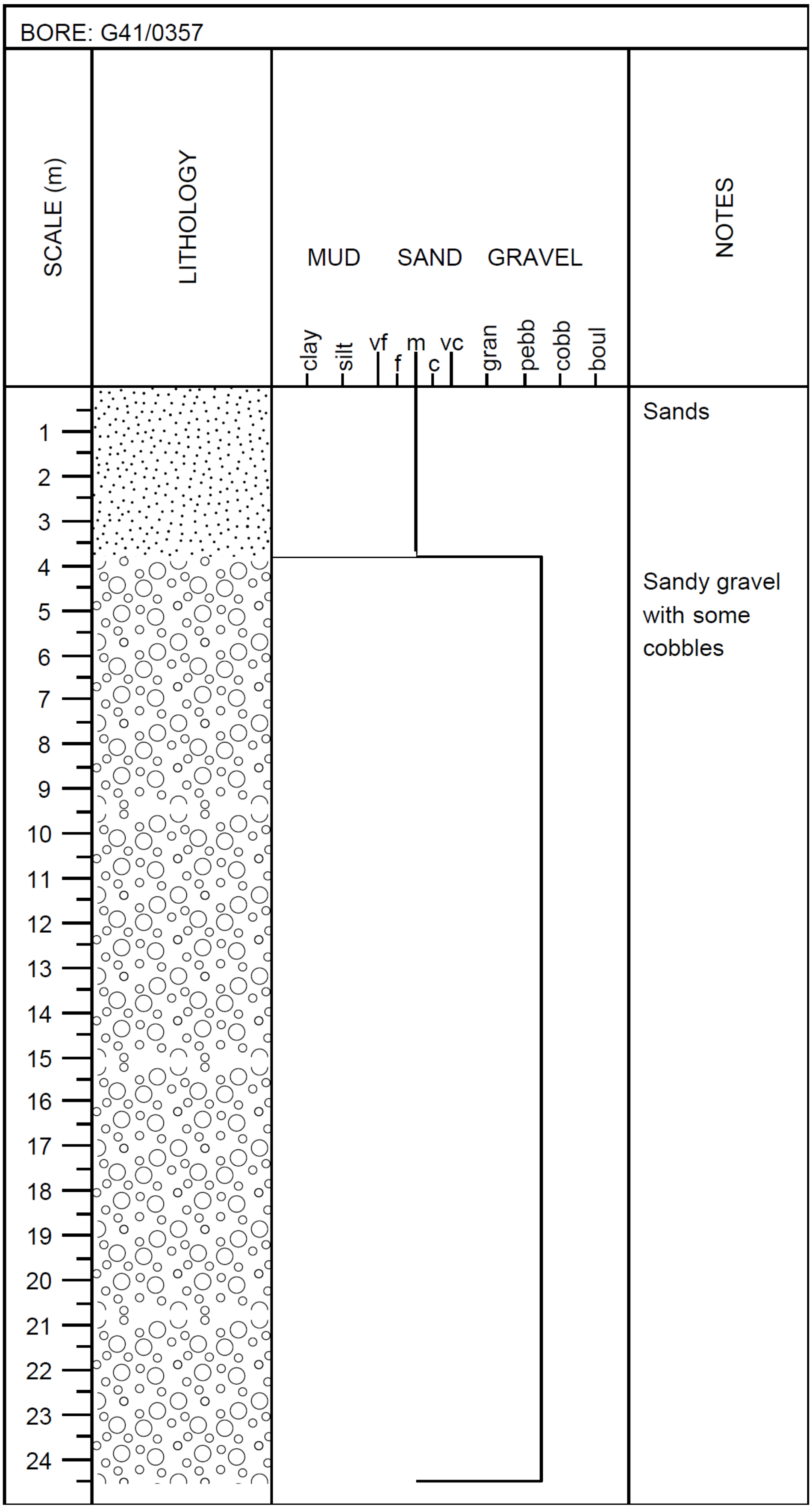
25
26
Sandy gravel.0.2m of Topsoil above gravel
Sandy gravel cobble


BORE: G41/0351
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Sandy brown gravel
Brown sand
Sandy gravel
Very sandy gravel
Sandy gravel
Very sandy gravel
Sandy gravel cobble


BORE: G41/0355
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Sands
Sandy gravel coarse with some cobbles


BORE: G41/0357
SCALE (m)
LITHOLOGY
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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17
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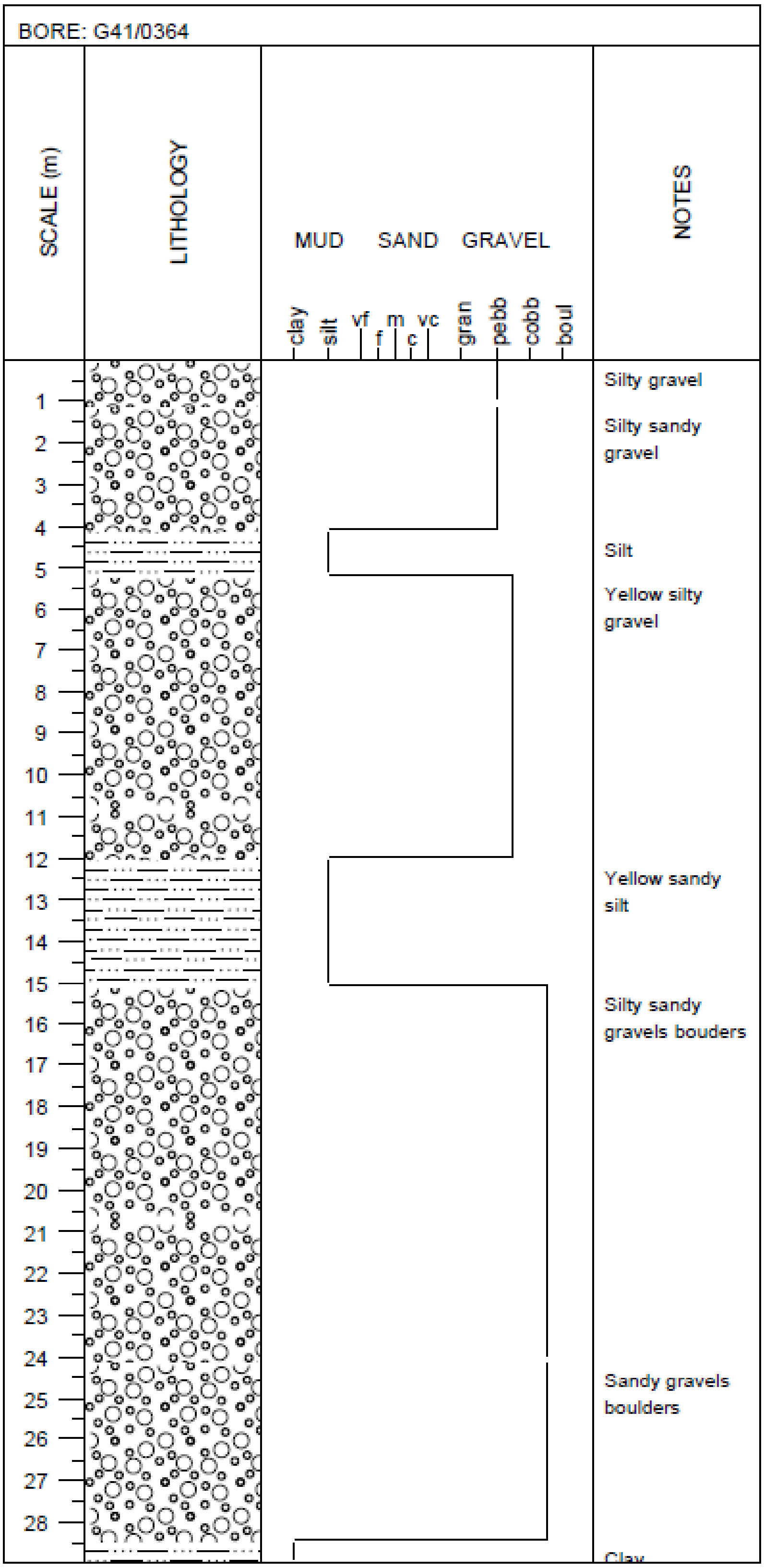
19
20
21
22
23
24
Sands
Sandy gravel
with some
cobbles


BORE: G41/0364
SCALE (m)
LITHOLOGY
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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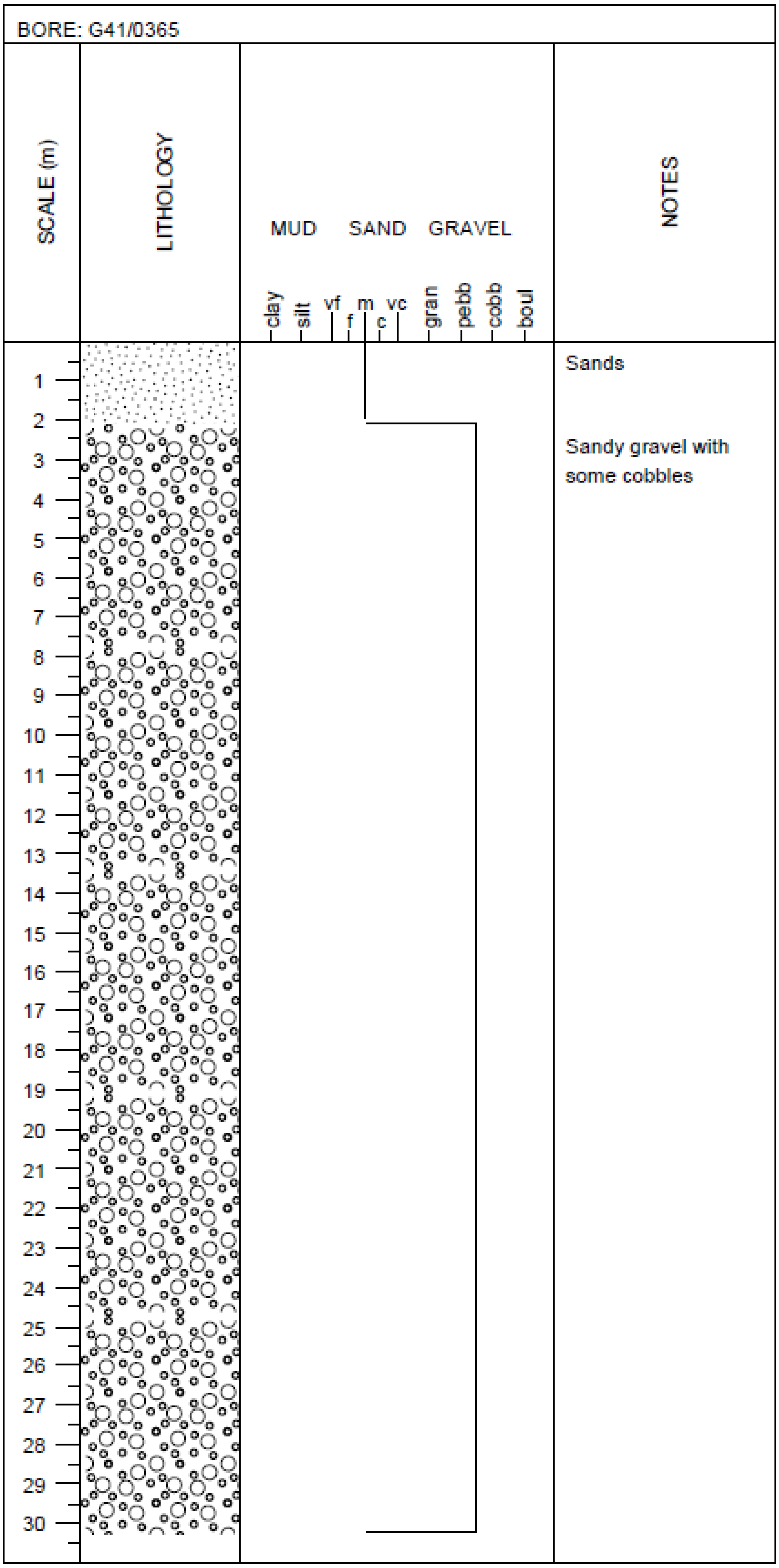
23
24
25
26
27
28
Silty gravel
Silty sandy gravel
Silt
Yellow silty gravel
Yellow sandy silt
Silty sandy gravels bouders
Sandy gravels boulders
Clay


BORE: G41/0365
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
Sands
Sandy gravel with some cobbles
1
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14
15
16
17
18
19
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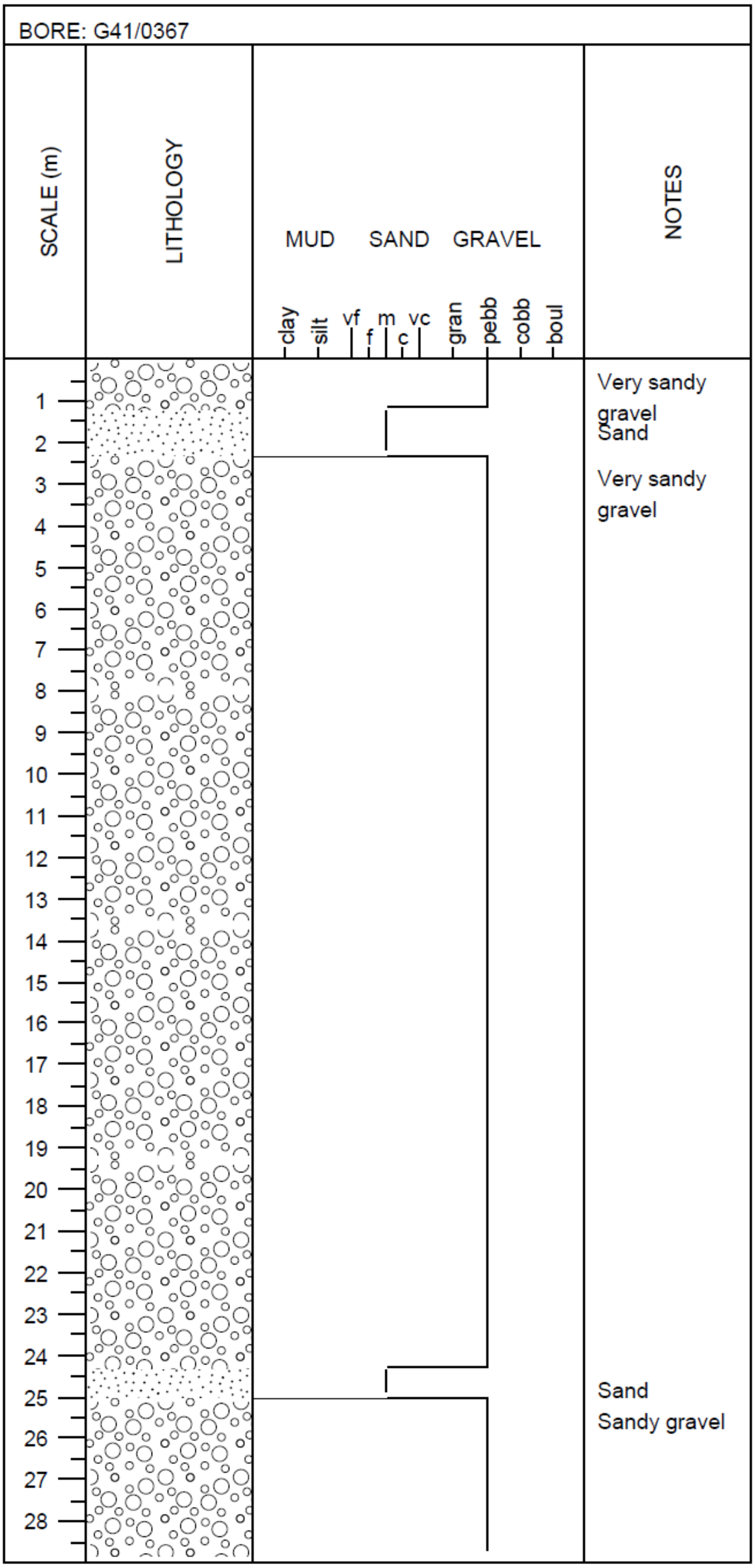
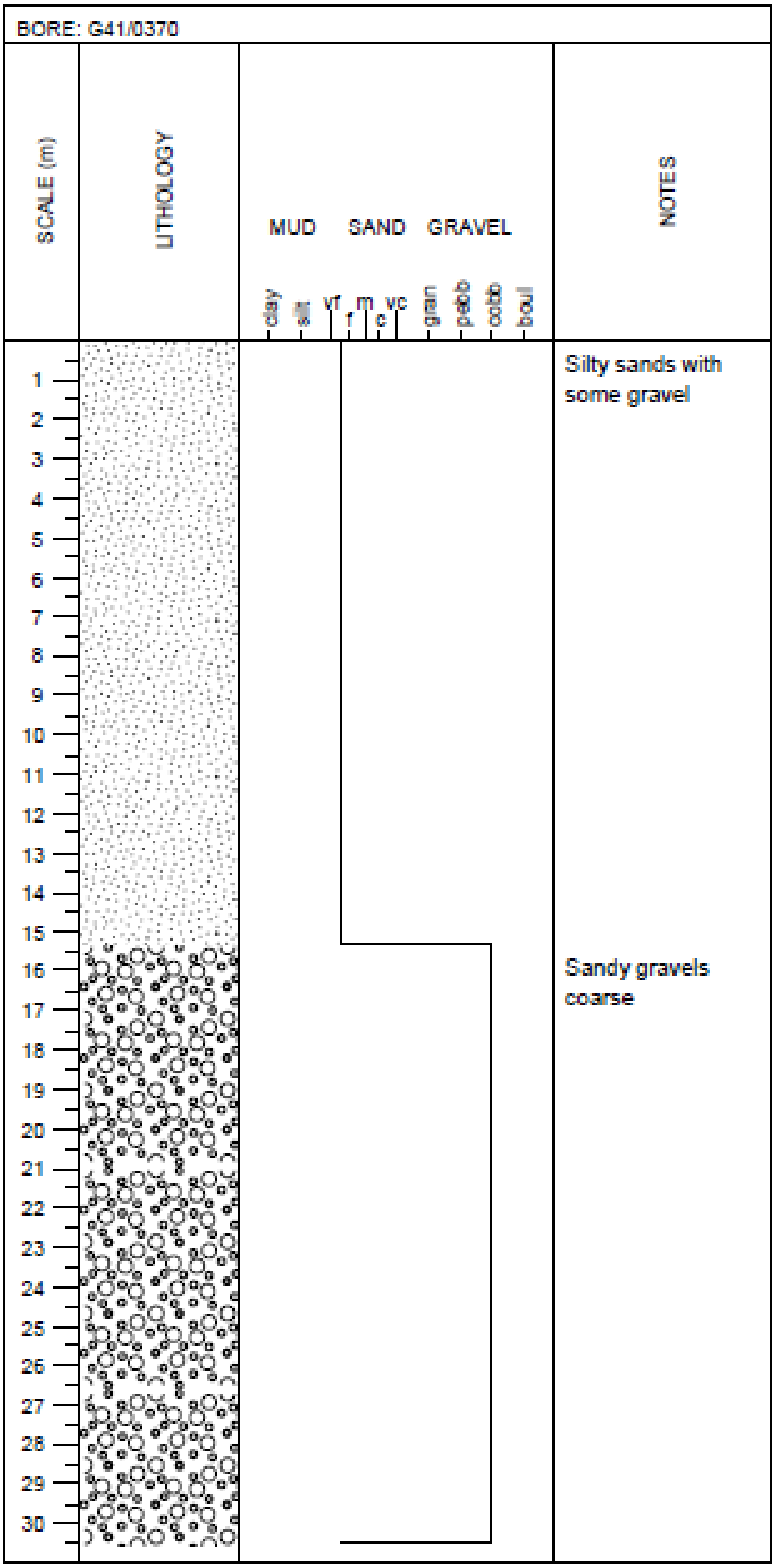
30


BORE: G41/0367
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
NOTES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Very sandy gravel
Sand
Very sandy gravel
Sand
Sandy gravel


BORE: G41/0370
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
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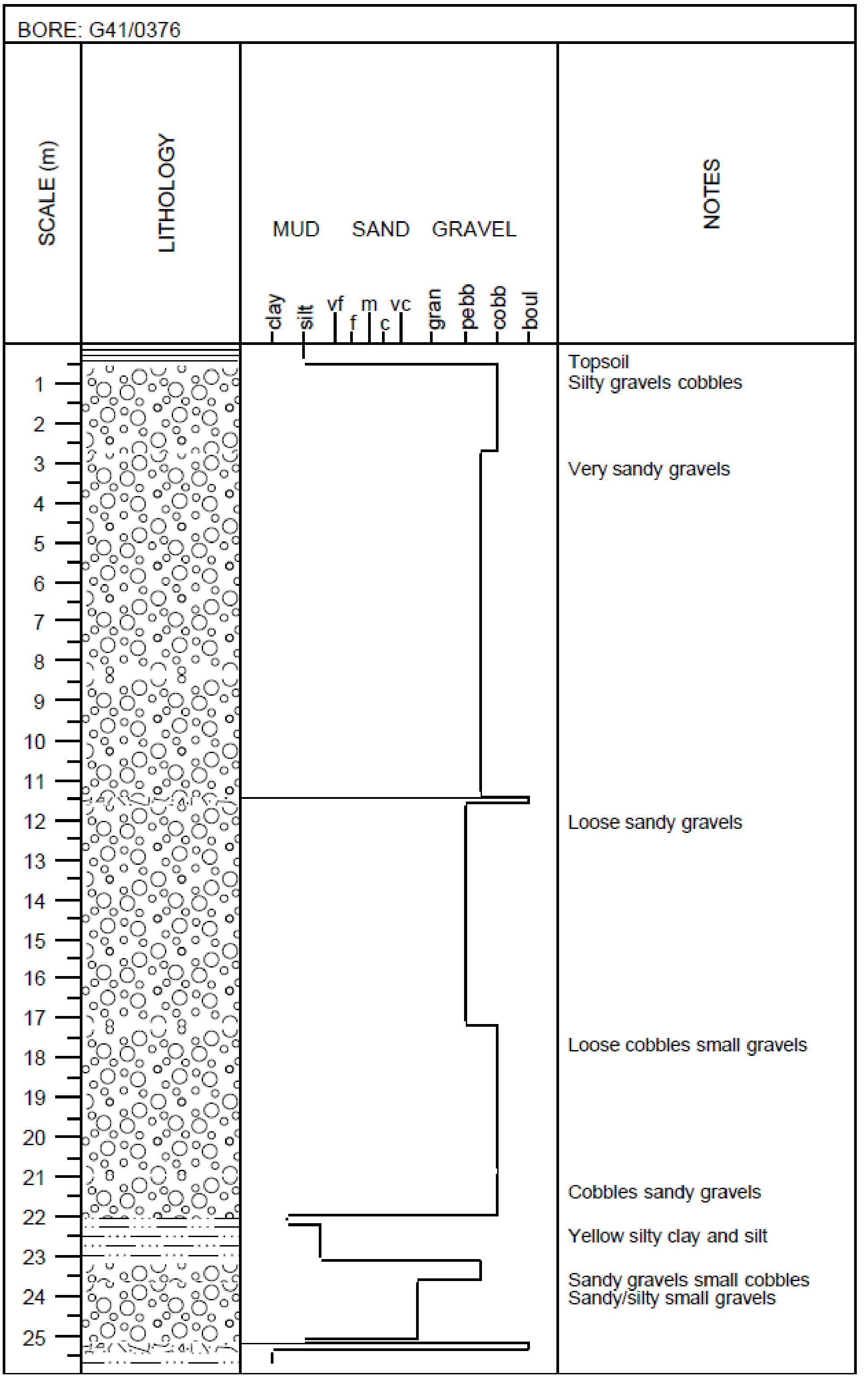
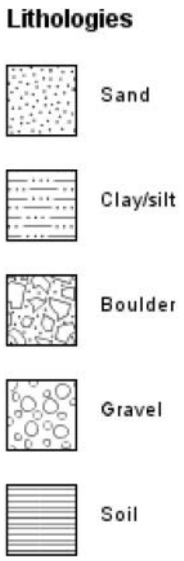
28
29
30
Silty sands with some gravel
Sandy gravels coarse


BORE: G41/0376
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
NOTES
Topsoil
Silty gravels cobbles
Very sandy gravels
Loose sandy gravels
Loose cobbles small gravels
Cobbles sandy gravels
Yellow silty clay and silt
Sandy gravels small cobbles
Sandy/silty small gravels

Bore log Legend



Appendix 4.3

"Sample location co ordinates, date of sampling and major cation and anion values in meq/L for samples from bores on the Cromwell Flat and Lake Dunstan and its tributaries"

All cation and anion values in meq/L

Bore/Site	F41/0138	F41/0155	F41/0168	F41/0223	F41/0226	F41/0247	F41/0261	F41/0297
Date of sampling	15-Dec-03	03-Nov-98	16-Dec-03	03-Nov-98	04-Nov-98	16-Dec-03	16-Dec-03	15-Dec-03
Easting	1299060	1296645	1299928	1297241	1297932	1298357	1298977	1297270
Northing	5002094	5002627	5003388	5004178	5003469	5005711	5004302	5002391
Ca	1.35	1.85	2.25	4.24	3.34	2.20	3.19	1.40
Mg	0.44	0.50	0.45	1.48	0.99	1.40	1.15	0.36
Na	0.30	0.17	0.43	0.87	0.20	0.65	0.70	0.27
K	0.03	0.06	0.05	0.05	0.04	0.03	0.05	0.04
CO3	0.03	0.00	0.03	0.00	0.00	0.03	0.03	0.03
HCO3	2.26	2.30	3.21	5.41	4.26	4.25	4.72	2.15
Cl	0.04	0.06	0.10	0.24	0.04	0.08	0.20	0.08
SO4	0.11	0.19	0.13	1.15	0.15	0.21	0.41	0.16
NO3	0.01	0.05	0.07	0.11	0.05	0.07	0.26	0.07
Fe	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
P	0.0008	0.0006	0.0008	0.0002	0.0002	0.0008	0.0008	0.0008

Notes: A - Lake Wanaka Outlet, B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D Kawarau Bridge (Bungy), E - Lake Wakatipu (Kawarau outlet)

All cation and anion values in meq/L

Bore/Site	F41/0300	G41/0177	G41/0246	G41/0256	A	B	C	D	E
Date of sampling	16-Dec-03	16-Dec-03	18-Sep-06	16-Dec-03	08-Feb-96	15-Dec-03	26-Jul-94	09-Aug-94	26-Jul-94
Easting	1297971	1302030	1300901	1300159	1294886	1300825	1265684	1276688	1263855
Northing	5003508	5005362	5006461	5006346	5047231	5004389	5008161	5007707	5005023
Ca	3.09	1.60	1.63	1.55	0.55	0.42	1.00	0.55	0.46
Mg	0.91	0.52	0.47	0.20	0.04	0.04	0.12	0.07	0.05
Na	0.20	0.37	0.35	0.22	0.03	0.10	0.07	0.06	0.07
K	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.02
CO3	0.03	0.03	0.07	0.03	0.00	0.03	-	-	-
HCO3	4.26	2.43	2.02	2.03	0.62	0.49	0.98	0.59	0.46
Cl	0.08	0.09	0.07	0.05	0.02	0.01	0.01	0.02	0.01
SO4	0.16	0.19	0.11	0.10	0.06	0.10	0.15	0.10	0.09
NO3	0.17	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	-	0.00	-	-	-
P	0.0008	0.0008	0.0015	0.0008	0.0002	0.0008	-	0.0002	-

Notes: A - Lake Wanaka Outlet, B - Lake Dunstan (Kawarau Arm), C - Shotover River (State Highway Bridge), D Kawarau Bridge (Bungy), E - Lake Wakatipu (Kawarau outlet)

Appendix 4.5

"Guideline and Maximum Acceptable Values for selected determinands based on the Drinking Water Standards for New Zealand 2005 (Revised 2008) (Ministry of Health, 2008)"

Determinand in milligrams per litre (mg/L) unless specified	Maximum Guideline Value (or Acceptable Range) on basis of aesthetic effects	Maximum Acceptable Value (MAV) on basis of health effects
pH	6.5 to 8.5 (preferred range between 7.0 and 8.0)	
Nitrate – Nitrogen		11.3
Sodium	200	
Iron	0.2	
Manganese	0.05	0.5
Sulphate	250	
Chloride	250	
Hardness	200	

Appendix 4.7

“Major cation and anion converted from milliequivalents per litre (meq/L) to percentage weights”

	Cations				Anions			
Bore/Site	**Ca %**	**Mg %**	**Na %**	**K %**	**HCO_3 %**	**Cl %**	**CO_3 %**	**SO_4 %**
F41/0138	63.61	20.98	13.96	1.45	92.48	1.73	1.36	4.43
F41/0155	71.78	19.51	6.43	2.29	90.03	2.54	0.00	7.43
F41/0168	70.63	14.24	13.68	1.45	92.22	2.99	0.96	3.82
F41/0223	63.87	22.30	13.10	0.73	79.62	3.53	0.00	16.85
F41/0226	73.02	21.57	4.46	0.95	95.90	0.82	0.00	3.28
F41/0247	51.36	32.72	15.26	0.66	92.54	2.15	0.73	4.58
F41/0261	62.74	22.63	13.67	0.95	87.99	3.78	0.62	7.60
F41/0297	67.36	17.45	13.21	1.97	88.99	3.16	1.38	6.47
F41/0300	72.88	21.32	4.71	1.08	93.83	1.86	0.73	3.57
G41/0177	63.28	20.54	14.65	1.52	88.35	3.39	1.21	7.05
G41/0246	65.65	19.03	14.20	1.12	89.20	3.03	2.95	4.82
G41/0256	77.66	9.91	11.14	1.28	91.76	2.04	1.50	4.70
A	85.40	6.40	5.41	2.79	88.44	2.40	0.00	9.16
B	79.73	9.56	8.85	1.86	82.99	2.38	0.00	14.64
C	82.82	9.54	6.14	1.49	85.86	1.22	0.00	12.91
D	72.57	6.84	17.32	3.28	77.45	2.22	5.25	15.08
E	78.12	8.31	10.98	2.58	81.28	2.50	0.00	16.22

Appendix 4.8

'Raw Deuterium and Oxygen 18 data for Cromwell Flat and Lake Dunstan'

Sample #	Easting	Northing	δ^2H (VSMOW)	$\delta^{18}O$ (VSMOW)	Date	Sample type
001	1302786	5002280	-55.0	-7.9	6/04/2010	Lake Dunstan
002	1301740	5006168	-53.1	-7.9	6/04/2010	Lake Dunstan
003	1301713	5004454	-53.9	-8.0	6/04/2010	Lake Dunstan
004	1300280	5004225	-57.7	-8.6	6/04/2010	Lake Dunstan
005	1300504	5003111	-56.7	-8.3	6/04/2010	Lake Dunstan
006	1296528	5002519	-57.2	-8.3	6/04/2010	Lake Dunstan
007	1296264	5003149	-52.2	-6.9	6/04/2010	Irrigation canal/pond
008	1302073	5005375	-56.7	-8.1	6/04/2010	Cromwell Town Supply
009	1297025	5003528	-54.6	-8.1	6/04/2010	Irrigation canal/pond
010	1296230	5003370	-55.9	-7.8	6/04/2010	Irrigation canal/pond
011	1309466	4990799	-55.1	-7.9	6/04/2010	Lake Dunstan
012	1302014	5005284	-53.2	-7.9	6/04/2010	Lake Dunstan
013	1301133	5007685	-53.5	-7.8	6/04/2010	Lake Dunstan
014	1298786	5008307	-69.1	-9.3	6/04/2010	Pisa Range stream
015	1297533	5006579	-69.9	-9.3	6/04/2010	Pisa Range stream
016	1301122	5007184	-52.5	-8.3	11/05/2010	Lake Dunstan
017	1297244	5006772	-69.4	-9.9	11/05/2010	Pisa Range stream
018	1297320	5006735	-69.1	-9.6	11/05/2010	Pisa Range stream
019	1297371	5006681	-71.1	-10.1	11/05/2010	Pisa Range stream
020	1299031	5005689	-44.2	-4.7	11/05/2010	Irrigation canal/pond
021	1299102	5005577	-67.8	-9.7	11/05/2010	Groundwater (F41/0252)
022	1297272	5002398	-60.5	-9.0	11/05/2010	Groundwater (F41/0361)
023	1300467	5006757	-70.2	-10.5	11/05/2010	Groundwater (G41/0160)
024	1301122	5007184	-68.9	-9.6	12/05/2010	Groundwater (G41/0224)
025	1296645	5002627	-58.4	-8.8	12/05/2010	Groundwater (F41/0155)
027	1300973	5006300	-70.6	-10.3	12/05/2010	Groundwater (G41/0370)
028	1297934	5003474	-59.5	-8.6	12/05/2010	Groundwater (F41/0171)
030	1300159	5006346	-72.2	-10.3	12/05/2010	Groundwater (G41/0256)
031	1301333	5006424	-67.9	-9.4	12/05/2010	Groundwater (G41/0365)
032	1302071	5005659	-56.1	-7.7	13/05/2010	Rainwater (Cromwell Flat)
033	1299388	5002100	-68.4	-9.4	13/05/2010	Groundwater (F41/0337)
034	1300972	5005117	-64.8	-9.4	13/05/2010	Groundwater (Unknown)
035	1296484	5005654	-68.8	-9.6	13/05/2010	Pisa Range stream
036	1297079	5006258	-67.7	-9.7	13/05/2010	Pisa Range stream
037	1301175	5006557	-73.4	-10.6	13/05/2010	Groundwater (G41/0371)
038	1301558	5006306	-65.2	-9.4	13/05/2010	Groundwater (G41/0351
039	1297606	5002355	-61.3	-9.0	13/05/2010	Groundwater (F41/0350)
041	1302073	5005375	-55.6	-8.4	14/05/2010	Cromwell Town Supply
042	1295868	5005539	-49.6	-7.0	14/05/2010	Rainwater (Pisa Range)
045	1296289	5006387	-56.2	-8.0	14/05/2010	Rainwater (Pisa Range)
058	1298357	5005711	-58.1	-8.5	9/08/2010	Groundwater (F41/0168)

(Continued over page)

Appendix 4.8 Continued

Sample #	Easting	Northing	$\delta^{2}H$ (VSMOW)	$\delta^{18}O$ (VSMOW)	Date	Sample type
060	1295503	5005436	-68.6	-9.4	10/08/2010	Snow (Pisa Range)
061	1295438	5006353	-81.3	-11.5	10/08/2010	Snow (Pisa Range)
062	1295403	5006669	-67.3	-9.6	10/08/2010	Snow (Pisa Range)
063	1295427	5006922	-69.0	-10.1	10/08/2010	Snow (Pisa Range)
064	1295473	5007387	-81.1	-11.2	10/08/2010	Snow (Pisa Range)
065	1295538	5008071	-94.3	-12.6	10/08/2010	Snow (Pisa Range)
066	1295536	5008476	-60.8	-8.5	10/08/2010	Snow (Pisa Range)
067	1295317	5008999	-66.3	-9.7	10/08/2010	Snow (Pisa Range)
068	1295073	5009551	-69.1	-10.5	10/08/2010	Snow (Pisa Range)

Appendix 5.3

'Water balance calculations for the Cromwell Terrace Aquifer'

Water Balance – Cromwell Flat

Simple water balance equation: <u>Inflow + Change in Storage = Outflow</u>

Surface area of Cromwell Flat = 24,000,000 m^2 (surface area extent of Cromwell Flat shown in figure 5.5.1)

Surface area of Pisa Range and foothills = 20,780,000 m^2 (surface area extent of Pisa Range and Foothills shown in figure 3.1)

Surface area of snow covered Pisa Range (August 2010) = 6,570,000 m^2

Average annual precipitation (Cromwell Flat) = 0.4396 m/yr (annual average for the period 1970 – 2000 (NIWA 2010))

Average annual evaporation (Cromwell Flat) = 1.4301 m/yr (annual average for the period 1985 – 2005 (NIWA 2010)) – Total evaporation from raised pan

Average annual evapotranspiration (Cromwell Flat) = 0.0042m/yr (annual average for the period 1984 -2007)

Inflows

Precipitation:

Cromwell Flat: Volume of precipitation for one hydrological year.

24,000,000 m^2 x 0.4396 m/yr

= 10,550,400 m^3/yr

Pisa Range and foothills: Volume of precipitation for one hydrological year.

20,780,000 m^2 x 0.4396 m/yr

= 9,134,888 m^3/yr

Total precipitation (Cromwell Flat + Pisa Range and foothills):

= 10,550,400 m^3/yr + 8,718,809 m^3/yr

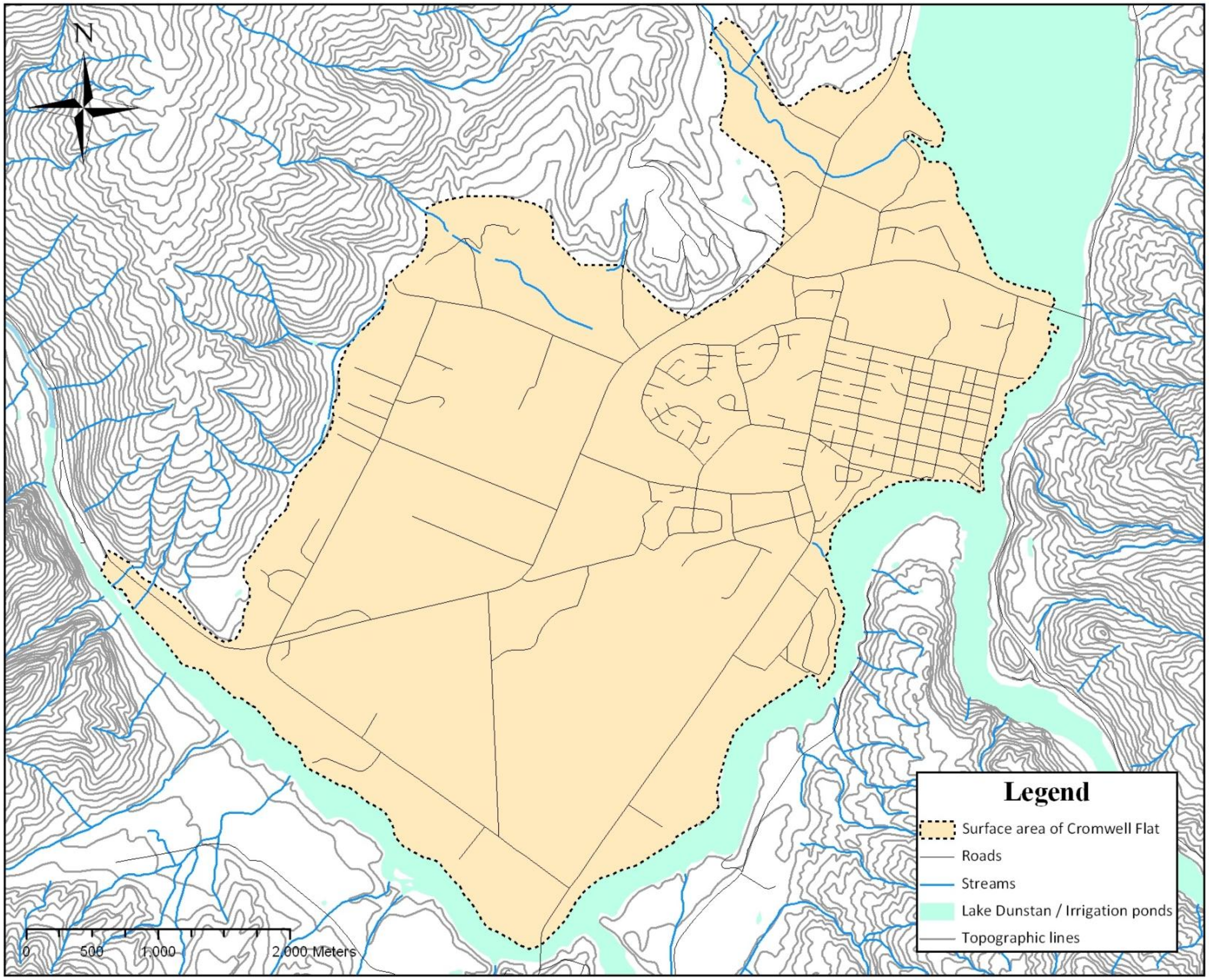
= <u>19,685,288 m^3/yr</u>

Surface Flows off Pisa Range:

3 active streams
Average flow rate for 1 stream = 0.00034 m^3/s (Measured May 2010 – minimum flow rate)

0.00034 m^3/s x 60s = 0.00204 m^3/min

Figure 5.5.1 – Map showing the approximate surface area of the Cromwell Flat used in the water budget calculations and cross section used for calculating outflow into Lake Dunstan. The surface are of the Flat is 24,000,000 m².



$0.00204 \text{ m}^3/\text{min} \times 60 \text{ min} = 1.224 \text{ m}^3/\text{hour}$

$1.224 \text{ m}^3/\text{hour} \times 24 \text{ hour} = 29.376 \text{ m}^3/\text{day}$

$29.376 \text{ m}^3/\text{day} \times 365 \text{ day} = 10{,}722.24 \text{ m}^3/\text{yr}$

3 streams = $10{,}722.24 \text{ m}^3/\text{yr} \times 3$

= $\underline{32{,}166.72 \text{ m}^3/\text{yr}}$

Snowfall and SWE on Pisa Range:

Snowfall on the Pisa Range was measured as SWE (Snow Water Equivalent) which is the depth of water from which the snow would melt down to.

Average SWE for snow on Pisa Range August 2010 = 23.701 L/m^2

Convert L to m^3: $(23.701 \text{ L/m}^2) / 1000 = 0.023701 \text{ m}^3/\text{m}^2 = 0.023701 \text{ m}$

SWE x Area: $0.023701 \text{ m} \times 6{,}570{,}000 \text{ m}^2$

= $\underline{155{,}715.6 \text{ m}^3/\text{yr}}$ (Assumed to be representable of snowfall for one hydrological year)

Ripponvale Water Scheme Irrigation:

Water extracted from Kawarau arm at Kawarau gorge exit

Water used for irrigation and domestic purposes. Irrigated water is considered artificial recharge.

Total area of land irrigated = 3,935,947 m^2 (from Murphy and O.R.C., 2009)

Rate of irrigation using water extracted from Kawarau = 2.06 mm/day

= 0.00206 m/day

= $0.00206 \text{ m/day} \times 365 \text{ day} = 0.7519 \text{ m/yr}$

Total volume of irrigation (artificial recharge to CTA):

= $3{,}935{,}947 \text{ m}^2 \times 0.7519 \text{ m/yr}$

= $\underline{2{,}959{,}438.55 \text{ m}^3/\text{yr}}$

Outflows

Evaporation:

Cromwell Flat: Volume of evaporation for one hydrological year.

= 24,000,000 m^2 x 1.4301 m/yr

= 34,322,400 m^3/yr

Pisa Range and Foothills: Volume of evaporation for one hydrological year.

= 20,780,000 m^2 x 1.4301 m/yr

= 29,717,478 m^3/yr

Total evaporation:

= 34,322,400 m^3/yr + 29,717,478 m^3/yr

= <u>64,039,878 m^3/yr</u>

Extraction of Groundwater:

The O.R.C. requires resource consent for bores extracting groundwater at rates greater than 25 m^3/day. The volumes of groundwater these bores extract are recorded by the O.R.C. in their database. No consent is required for groundwater extractions less than 25 m^3/day.

Annual groundwater abstraction volume from bores extracting groundwater at rates >25 m^3/day for 20 bores (O.R.C., 2010):

= 3,203,489 m^3/yr

(These bores and volumes extracted are shown in appendix 5.3.1)

All other bores are assumed to be extracting the maximum 25 m^3/day. There are 22 remaining bores on the Cromwell Flat that are discussed in this study. These are all assumed to be actively used. The total volume of extracted groundwater is:

= 22 bores x 25 m^3/day

= 550 m^3/day x 365 days

= 200,750 m^3/yr

Total volume of groundwater extracted is:

= 3,203,489 m^3/yr + 200,750 m^3/yr

= <u>3,404,239 m^3/yr</u>

Evapotranspiration:

Cromwell Flat: Volume of evapotranspiration for one hydrological year.

= 24,000,000 m^2 x 0.0042 m/yr

= 100,800 m^3/yr

Pisa Range and foothills: Volume of evapotranspiration for one hydrological year.

= 20,780,000 m^2 x 0.0042 m/yr

= 87,276 m^3/yr

Total evapotranspiration:

= 100,800 m^3/yr + 87,276 m^3/yr

= 188,076 m^3/yr

Outflow into Lake Dunstan:

Outflow into Lake Dunstan was found using the Dupuit equation for determining steady flow in an unconfined aquifer (Fetter, 2001). The result is a flow rate per unit width which can then be multiplied by the width of the aquifer to give an estimate of the volume of groundwater flow out of the aquifer.

The Dupuit equation is given as:

$$q' = \tfrac{1}{2}K\left((h1^2 - h2^2) / L\right)$$

Where: q' = flow per unit width (m^2/day), K = hydraulic conductivity (m/day), h1 = head at origin (m), h2 = head at L (m), L = flow length. (Figure 5.5.2)

For the CTA:

Change in head and flow length is from bore F41/0247 to G41/0133 as shown in the hydrogeological cross-section A-B (figure 3.6 in thesis)

K = 55 m/day (MWH NZ Ltd, 2007)

h1 = 32 m

h2 = 8 m

L = 2550 m

q' = ½55 m/day x ((32 m^2 - 8 m^2) / 2550 m)

q' = 27.5 m/day x (960 / 2550 m)

q' = 27.5 m/day x (0.376 m)

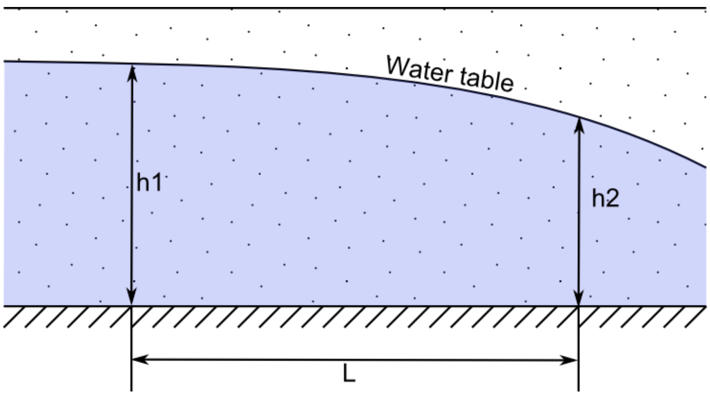


Figure 5.5.2 - Diagram showing steady flow through an unconfined aquifer with parameters used in Dupuit's equation (Adapted from Fetter, 2001).

q' = 10.35 m²/day x 365 days

q' = 3,778.8 m²/yr

Flow rate found by multiplying q' by width of aquifer along line A'- B' (shown in figure 5.5.1)

Width of aquifer along line A'-B'= 6,610 m

Flow = 3778.8 m²/day x 6,610 m

= <u>24,978,024 m³/yr</u>

Hydrologic Continuity Equation for Average Annual Groundwater Flow

Annual Water balance for Cromwell Terrace Aquifer			
Inflow + Change in Storage(m³/yr)		**Outflow (m³/yr)**	
Precipitation	19,685,288	Evaporation	64,039,878
Surface flows	32,167	Groundwater extraction	3,404,239
SWE	155,716	Evapotranspiration	188,076
Irrigation (Kawarau)	2,959,439	Outflow into Lake Dunstan	24,978,024
Inflow from Pisa Range bedrock	x		
Total Inflow + Change in storage (m³/yr)	22,832,610 + x	**Total outflow (m³/yr)**	92,610,217

Groundwater inflow is assumed to coming from out of the fractures in basement schist of the Pisa Range at the back of the Cromwell Flat. The volume of the inflow is calculated indirectly via:

Inflow + Change in Storage = Outflow

22,832,610 m³/yr + x = 92,610,217 m³/yr

x = 92,610,217 m³/yr - 22,832,610 m³/yr

x = 69,777,607 m³/yr

Inflow from Pisa Range bedrock =<u>69,777,607 m³/yr</u>

Summarised Annual Water Balance for the CTA

Annual Water balance for Cromwell Terrace Aquifer			
Inflow (m³/yr)		**Outflow (m³/yr)**	
Precipitation	19,685,288	Evaporation	64,039,878
Surface flows	32,167	Groundwater extraction	3,404,239
SWE	155,716	Evapotranspiration	188,076
Irrigation (Kawarau)	2,959,439	Outflow into Lake Dunstan	24,978,024
Inflow from Pisa Range bedrock	69,777,607		
Total Inflow (m³/yr)	92,610,217	**Total outflow (m³/yr)**	92,610,217

Appendix 5.3.1

'List of bores with resource consents for extracting groundwater at rates >25 m³/day and bores without consent'

Bores consented to extract more than 25 m³/day.

Bore #	Groundwater use	Volume extracted per year (m³/yr)
F41/0252	Horticulture	86,400
F41/0262	Horticulture	7,776
F41/0245	Horticulture	74,160
F41/0268	Horticulture	18,000
G41/0224	Irrigation	43,200
G41/0246	Horticulture	400,000
G41/0256	Frost fighting	4,620
F41/0297	Irrigation, Communal water supply	45,490
F41/0138	Irrigation, Communal water supply	17,496
F41/0312	Horticulture	64,800
F41/0316	Irrigation, Single domestic supply	10,382
F41/0268	Frost fighting	6,681
-	Viticulture (Irrigation, Frost fighting)	8,400
F41/0350	Horticulture	258,720
F41/0308	Olive irrigation	15,400
G41/0364	Irrigation, Communal water supply	181,467
G41/0248	Irrigation	90,000
-	Irrigation	240,000
F41/0214	Bottling water	10,498
G41/0177	Cromwell water supply	1620,000
Total		**3,203,489**

(**Notes**: A dash (-) indicates unknown bore number)

Bores assumed to extract groundwater at <25 m³/day (25 m³/day x 365 days = 9125 m³/day).

Bore #	Volume extracted per year (m³/yr)
F41/0155	<9125
F41/0168	<9125
F41/0175	<9125
F41/0180	<9125
F41/0243	<9125
F41/0300	<9125
F41/0303	<9125
F41/0337	<9125
G41/0122	<9125
G41/0130	<9125
G41/0133	<9125
G41/0349	<9125
G41/0351	<9125
G41/0355	<9125
G41/0357	<9125
G41/0365	<9125
G41/0367	<9125
G41/0370	<9125
G41/0376	<9125
F41/0171	<9125
F41/0318	<9125
F41/0337	<9125
G41/0371	<9125
Total	**200,750**